An Integrated Sustainability Assessment of Cotton Cropping Systems in Punjab, Pakistan: Techno-Economic Performances, Environmental Impacts and Eco-efficiency Analysis

by

Asmat Ullah

A dissertation submitted in partial fulfillment of the requirements for
the degree of Doctor of Philosophy in
Natural Resources Management

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Acknowledgements

The Success of this research would not have been possible without the help and support of many people. First and foremost I would like to express my deepest gratitude to Dr. Sylvain R. Perret for providing continuous guidance and his consistent help and support to conduct this research. I feel deeply obliged to Dr. Perret for his mentorship and whose intellect and spirit inspired me throughout this research. It was indeed impossible to accomplish this study without his technical, editorial advice and support. I feel blessed to conduct my research under his supervision and I always received motivation and encouragement from him at critical moments.

My sincere appreciation and gratitude goes to esteemed members of examination committee, Prof. Shabbir H. Gheewala, Dr. Rajendra P. Shrestha and Dr. Peeyush Soni for their constructive comments and suggestions during this research. Prof. Gheewala has contributed substantially to this dissertation by providing guidance in the area of Life Cycle Assessment (LCA). Dr. Shrestha has provided me with the important and critical insights on crop and soil interactions. Dr. Soni provided me tremendous guidance on energy use in agriculture. This research would not have been complete without the diverse expertise of my committee members.

I would like to express my gratitude to Mr. Yannick Biard who has provided me with his valuable time and guidance regarding SimaPro and provided me remote access to the SimaPro platform at Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD). I would also like to extend my gratitude to Dr. Hayo M.G. van der Werf, Institut National de la Recherche Agronomique (INRA) the French National Institute of Agronomic Research, for kindly agreeing to review my dissertation as an external examiner. I feel honoured to acknowledge all these personalities.

I am very thankful to the Higher Education Commission (HEC), Pakistan for providing me doctoral study support. This study would not have been possible without the financial support of HEC. I am indebted to Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), the French Agricultural Research Centre for International Development for providing me the opportunity to use SimaPro to analyze and conduct my research and providing me the financial support to attend various conferences and SimaPro training in the Netherlands.

Many thanks to those farmers who have spent hours with me and provided me detailed information regarding their cotton crop production practices. Here I would like to thank all my friends for their help and the wonderful time I have spent with them. My special thanks go to Kwansirinapa Saratis with whom I have always used to exchange ideas and get help regarding this research. I am very thankful to Dr. Akhatar Nawaz Khan, Dr. Arshad Mehmood, Dr. Robinson Mariyasoosai and Stephanie Li Choo for their individual contribution in my research.

Last, but not least, I would like to thank all my family members for their support and encouragement throughout my life and especially during my stay in Thailand. My parents receive my deepest gratitude and love for their dedication and the many years of support during my studies that provided the foundation for this work.

Abstract

Cotton cropping in Pakistan generates rural employment and income, and export revenues. It also utilizes substantial amounts of water and energy resources, and adversely affects the environment with pollutants from inputs, especially pesticides, fertilizers, and emissions from non-renewable energy use. There is a need to assess the sustainability of cotton production systems, which may be achieved through more reasonable use of inputs and resources, hence less environmental impacts, combined with sustained income for farmers.

This research investigates the possibility of meeting such challenge by studying existing cropping systems from an integrated, multi-criteria perspective. It analyzes their techno-economic performances and efficiency, along with their environmental impacts. A specific focus is paid to the farm size as a possible factor to performances, impacts and efficiencies. The sources of high environmental impacts and of inefficiencies have also been examined.

The research was mostly based upon primary data that was collected from 169 farmers in the southern part of the Punjab province of Pakistan. The environmental impacts have been analyzed through Life Cycle Assessment (LCA) methodological approach, and also with an alternative approach to environmental impact analysis using farm-level ad-hoc indicators. LCA based potential environmental impact indicators result from the use of CML characterisation method; they are: abiotic resources depletion (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), human toxicity potential (HTP), terrestrial ecotoxicity potential (TETP) fresh water aquatic ecotoxicity potential (FETP) and water use (WU). The farm level ad-hoc indicators are: water use, energy ratio, nitrogen balance, phosphorus balance and pesticides risks. Through these sets of indicators, technical, cost and environmental efficiencies have been estimated by non-parametric Data Envelopment Analysis (DEA) procedure. All these efficiencies estimates have been separately regressed with some specific contextual variables to identify the sources of inefficiencies.

Results first highlight the high variability in cropping practices, input and resource utilization patterns, and environmental impacts that exist in cotton cropping systems in Punjab. With regards to factor productivities and farm size, large farms perform better for all production factors, except for pesticide productivity, which is higher in small farms. With regards to environmental impacts, it was observed that field emissions from pesticides and fertilizers are the largest contributors. LCA results as per kg of seed cotton at farm gate are: GWP 3.15 ($\pm$1.29) kg CO_2-eq, AP 0.051($\pm$0.018) kg SO_2-eq, EP 0.056 ($\pm$0.027) kg PO_4-eq, HTP 2.78 ($\pm$1.41) kg 1,4-DB-eq, FETP 5.45 ($\pm$6.86) kg 1,4-DB-eq and WU 5.16 ($\pm$1.91) m^3. No significant difference was observed among farm size groups except for EP and WU where small farms show significantly higher value of EP and WU.

Overall, farms show relatively high technical and cost efficiencies. Yet, results contradict the findings on factor productivities since small farms perform slightly better than others: the mean technical efficiency scores are 0.96, 0.92, and 0.91 for small, medium and large farms, respectively; mean cost efficiency scores are 0.84, 0.77 and 0.80 for small, medium and large sized farms, respectively.

From environmental perspective, the results reveal that farmers are broadly environmentally inefficient, irrespective of farm size, yet with serious differences according the method used. Based on farm-level ad-hoc indicators, the environmental efficiency scores are 0.93, 0.87 and 0.89 for small, medium, and large farms, respectively. Eco-efficiency estimates through Life Cycle Assessment (LCA) indicators computed on

per hectare basis are 0.84, 0.70 and 0.77, respectively, and 0.49, 0.50 and 0.48 respectively when computed on the basis of kilogram of seed cotton. Moreover, differences in technical and environmental efficiencies across different farm sizes were found to be statistically significant at 5%, on per hectare basis. Cost efficiency differences across different farms were found statistically significant at 10%. However, no statistically significant difference of eco-efficiency was found when expressed on per kilogram of seed cotton.

Besides efficacy scores, DEA analysis also revealed the potential reduction of input and resource use for non-efficient systems to meet full efficiency as per production frontier curve. Variability in the percentage of potential reduction of pesticides is observed (between 22 to 40%), potential reduction of nitrogen varies between 22 to 31%, and potential reduction of water use varies in the range of 12% to 16%. The variability of input uses lead to variable environmental impacts per kilogram of seed cotton among different farm sizes. The second stage regression analysis with contextual variables identifies that plot size and raised-bed (ridge) sowing methods have significant and negative effects on efficiencies whereas exposure to extension and training affects positively. Paradoxically, formal education level is found to negatively affect efficiencies.

The differences in mean efficiencies among farms are mostly explained by varying levels of water use, nitrogen fertilizers and pesticides applications. Towards concrete action and increased sustainability, selection of target inputs for reduction measures should first establish stakeholders' preferences (which impacts or cost to reduce? which input or resource to spare?), based on weighting and normalization of environmental impacts, and on thorough assessment of trade-offs between impact and cost reductions, and expectations in terms of yields.

A sustainability analysis was carried out, looking for farms that would epitomize sustainable cotton production by showing high economic performance and low environmental impacts. Two approaches have been used at the cropping system level: a comparison of technical, economic and environmental performances, and a comparison of efficiency scores. Both approaches show that such match between high techno-economic and environmental performances proves extremely rare. The findings demonstrate that sustainability in cotton production in Punjab refers to an inescapable trade-offs since it proves almost impossible to combine high economic return with low environmental impacts under current context, technology, patterns, and objectives. However some recommendations could be formulated with regards, to pesticides and fertilizers use by farms, which uses may be significantly reduced with no effect on yield, and with potential positive reduction of environmental impacts.

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List of Acronyms

AP	Acidification Potential
CRS	Constant Return to Scale
CWR	Crop Water Requirement
DAP	Diammonium Phosphate
DEA	Data Envelopment Analysis
DMUs	Decision Making Units
EE	Environmental efficiency
EP	Eutrophication Potential
ETa	Actual Crop Evapotranspiration
ETo	Reference Crop Evapotranspiration
FAETP	Freshwater Aquatic Ecotoxicity Potential
FAO	Food and Agriculture Organization of the United Nations
FU	Functional Unit
GDP	Gross Domestic Product
GHG	Green House Gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
IWR	Irrigation Water Requirement
Kc	Crop coefficient
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NIRS	Non-increasing return to scale
ODP	Ozone Depletion Potential
SE	Scale efficiency
TE_{CRS}	Technical efficiency by constant return to scale
TE_{VRS}	Technical efficiency by variable returns to scale
USDA	United States Department of Agriculture
VRS	Variable Return to Scale
VW	Virtual water
WU	Water Use

List of Symbols

eq	Equivalent
ha	Hectare
kg	Kilogram
kg Sb-eq	Kilogram Antimony equivalent
kg CO_2-eq	Kilogram carbon dioxide equivalent
kg SO_2-eq	Kilogram sulphur dioxide equivalent
kg PO_4^{3-} eq	Kilogram phosphate equivalent
kg 1,4-DB eq	Kilogram 1,4 dichlorobenzene equivalent
kg CFC-11 eq	Kilogram trichlorofluoromethane equivalent
kg C2H4 eq	Kilogram ethylene equivalent
MJ	Mega Joule
N_2O	Nitrous Oxide
N	Nitrogen
NO	Nitrogen Oxide
NH_3	Ammonia
P_2O_5	Phosphorus
K_2O	Potassium
$	US dollar
θ	Technical efficiency score
ϑ	Environmental efficiency score
$\hat{\theta}$	Bootstrapped technical efficiency score
$\hat{\vartheta}$	Bootstrapped environmental efficiency score
λ	Intensity vector of weight of weights

Chapter 1

Introduction

1.1 Background

Agriculture is a predominant sector of the economy of Pakistan. Total contribution of agriculture to Gross Domestic Product (GDP) is 21.4 percent and 45 percent of the total employed labor force is engaged with this sector for their livelihood. The average growth rate of agriculture is 3.3 percent per annum. About 80% of agriculture in Pakistan is irrigated as the climatic condition of the country is arid and semi-arid. Indus Basin Irrigation System (IBIS) plays a vital role in the development of agriculture of the country. The Indus basin is the main contributor to the agricultural GDP through producing cash and export crops. The major crops include wheat, rice, cotton and sugarcane and contribute 25.2 percent to the value added to overall agriculture. (Economic Survey of Pakistan, 2012-13).

Cotton is a major nonfood cash crop of the country grown in summer season. It contributes 7.0 percent to the value added in agriculture and 1.5 percent to the GDP (Economic Survey of Pakistan, 2012-13). Pakistan produced 11.56 million bales from the cultivated area of 2,689.1 thousand hectares with an average yield of 731 kilogram cotton lint per hectare (Agricultural Statistics of Pakistan, 2010-11).

Worldwide approximately 31 million hectares (2.4 percent of arable land) are under cotton. About 20 million farmers are completely dependent on cotton production and 30 million farmers are dependent on cotton production in their rotation scheme (Kooistra et al., 2006). In Pakistan cotton is mainly grown in the southern part of the Punjab province and the upper part of Sindh province. There are two major cotton crops; conventional and genetically modified *Bacillus thuringiensis* (Bt) cotton. The Bt cotton is considered environmentally friendly as it is less susceptible to insect pest attack, requiring less chemical pesticides, in comparison to conventional cotton crops. Bt cotton occupies 80% of the total area under cotton in Punjab and Sindh province (Abid et al., 2011).

Cotton is a very important farming activity of Pakistan and it is the main source of foreign exchange earning of the country. Pakistan is experiencing a fluctuating trend in the cotton crop production due to different natural calamities and in the recent years declining trend of per hectare yield of seed cotton has been observed. In order to enhance the production of the crop, the farmers adopt different management practices such as sowing the crop on raised seedbed and manual planting. There is a range of various factors responsible for yield variation of cotton crop. Among those the physical factors are temperature, rainfall, low soil fertility and salinity and biological factors are insect pest invasion, diseases and weeds prevalence. Beside that different varieties of seed and farmers' socioeconomic factor such as experience, knowledge of adopting best management practices are also responsible for yield variation.

In Pakistan cotton is grown mainly on flat seed-beds and is then irrigated through flood irrigation method, or it is grown on ridges and furrow irrigation is practiced. Canal water is the main source of irrigation however groundwater is also exploited even if the ground water is saline in most of the cotton production area of Pakistan. The use of saline water worsens the soil salinity issue as there is no sufficient surface water to flush down the salt from the root zone of the crop. Water logging is another problem caused by mismanagement of irrigation water. Application of chemical fertilizers is very common due to low soil fertility. Pesticides are also used in order to control pest attacks. The excessive use of nitrogen fertilizers cause various emissions to air, soil and water in the form of nitrous oxide, nitric oxides and nitrate. These are the damaging environmental impacts and the magnitude of these environmental impacts varies depending upon the farm management practices and soil and climatic conditions (Choudhury and Kennedy, 2005).

1.2 Statement of the problem

The quantity of farm inputs such as the volume of irrigation water, doses of agro-chemicals, labor hours and mechanical energy in the form of electricity and fossils fuels (i.e. the input-related impacts of cotton production) varies depending upon the environmental conditions, type of cotton grown as well as the socio economic condition of the farmers of a particular locality. However modern production tends to mobilize tremendous amounts of inputs. The haphazard use of resources can affect the surrounding environment and ultimately the society will be negatively affected.

Cotton crop needs a huge amount of irrigation water. In the areas where the natural precipitation is lower than water requirements of the cotton crop, river water is diverted or groundwater is pumped. In such a situation the water will not be available for downstream users and the groundwater table will also be lowered if depletion surpasses replenishment. On the other hand the high water requirement of cotton production in arid context is conducive to salinization if evapo-transpiration exceeds rainfall. Synthetic fertilizer is another major input in cotton production. The crop growth and the environmental impact of fertilizers depend upon the pattern of rainfall, type and amount of fertilizer use as well as the timing of the application of fertilizer. In order to protect the cotton crop from insect and pest attacks, heavy amounts of pesticides are used. The freshwater resources, surface as well as groundwater, are constantly being contaminated due to overuse and misuse of chemical pesticides in cotton growing area of Pakistan (Tariq et al., 2007). The demand of fossil fuel is also increasing due to technological advancement in agriculture sector not only at farm level but also at the inputs manufacturing, processing and transportation stages.

The global demand of ecofriendly products is increasing as western countries require increasingly certified and/or labeled products. Eco friendly products ensure less impact on the resources depletion as well as less negative impacts on the surrounding environment and Pakistan is a major exporter of cotton. Most of the chemical pesticides used in the cotton crop are harmful to life on earth. Heavy use of pesticides contaminates surface water and groundwater. In order to sustain the farmers' income and local livelihood, the farm inputs need to be optimized at a sustainable level along with enhanced land productivity. It can be attained with the adoption of best management practices through lesser non-renewable energy use and freshwater use for the crop production system. Therefore the assessment of energy consumption pattern, agro-chemicals use and water use is necessary in cotton production systems.

1.3 Rationale of the study

Cotton being the major cash crop of the country depends on the heavy use the resources (water, energy, labor, fertilizers, pesticides and land) and adversely affects the environment through depleting water resources and soil fertility, salinization, desertification and has negative impacts on the surrounding fauna and flora through poisoning of the environment. In many countries especially in the developing world the use of pesticides is not regulated or monitored properly and the same is true in the case of Pakistan. In order to ensure more ecofriendly cotton production and sustainable management of the resources the technical, environmental and agronomic dimensions of cotton crop should be considered in an integrated manner. It may be hypothesized that meeting simultaneously high economic return and low environmental impacts is not possible, trade-offs are necessary, and an overall improvement of cropping systems in sought-after toward sustainability.

To meet the pending options and challenges, this research investigated both environmental and techno-economic performances of cotton cropping in Pakistan in an integrated manner. It tried to identify the trade-offs between high economic returns and low environmental impacts from real farm data and practices. The goal was to identify hotspots of pollutions, emissions or resources use along the chain of cotton production. The research also aimed to document and informs current debate on adoption of eco-friendly practices and eco labeling through environmental friendly resources management. An analysis of possible best practices toward reasonable use of inputs and resources was conducted in order to enhance cotton productivity without any serious harm to the environment and to the society.

In order to achieve these goals and to address the sustainability challenges an integrated approach is favored. Techno economic analysis of cotton productions systems was combined with environmental impact analysis using farm level ad-hoc indicators and LCA approaches. Documenting environmental impacts through LCA may prove cumbersome and difficult for managers and practitioners. So the Idea was to check whether an alternative approach could help. This also includes eco-efficiency analysis which is defined as “the ratio of economic value added to it environmental impacts” (OECD, 1998). Eco-efficiency scores may be considered proxies to sustainability indicators.

1.4 Objectives of the study

The overall objective of this study is to investigate the environmental impacts and techno economic performances of selected cotton production systems in Pakistan, their relationship and to assess their eco-efficiency. A specific focus is paid to the farm size as a possible factor to performances, impacts and eco-efficiency. Also the diversity of farming situations is considered, with the analysis of a large number of systems.

The specific objectives are to:

1. Assess the technical and economic performances of the selected cotton cropping systems.
2. Assess the potential environmental impacts of selected cotton production systems with farm-level ad-hoc indicators and through life cycle assessment (LCA) approach.
3. Investigate the relationship between the potential environmental impacts and technical and economic performances of the selected systems, their technical and eco-efficiencies.
4. Identify the high environmental impact spots, best practices, and especially examine tradeoffs options between performances (productivities) and environmental impacts and to examine some options and feasibility conditions toward higher performance and lower environmental impacts.

1.5 Conceptual framework

The performances of cotton cropping systems are defined mainly in economic and environmental perspectives. Farmers' always focus to achieve maximum cotton yield and thus higher economic return with lesser concerns toward negative environmental impacts. However the demand of environmental friendly products is increasing. To produce eco-friendly product, considering the environmental impacts over a broader range is necessary (Keating et al. 2010). Conceptual framework of this research is shown in figure 1.1. Different inputs including irrigation water, energy and agrochemicals are used at different stages in cotton crop production systems and the quantities of these inputs varies from farm to farm depending upon the farmers' decisions and management practices. Due to the variation of the quantity of input used and the resources consumed, the amount of desirable output (yield) and undesirable outputs (environmental impacts) also vary. These variations ultimately lead to the various levels of technical, economic and environmental performances of cotton production systems. Analyzing these performances separately may help to improve that specific domain but it may not help to achieve a sustainable production of systems. Sustainability analysis is an approach, where performances indicators in technical, economic and environmental perspectives are required.

Acquiring sustainability of cotton cropping systems is a challenging task which needs the computation of potential environmental impacts along with the economic performances of the cotton cropping systems. The environmental performances of cotton cropping systems can be calculated based on different environmental impacts indicators. But to translate them into a single indicator and to integrate the environmental impacts with economic performance, eco-efficiency is the best possible option. Eco-efficiency is a possible approach which helps to assess if the individual farmers are utilizing minimum resources, producing lower environmental impacts while maintaining their economic returns (Gómez-Limón et al., 2012). Eco-efficiency is an approach, which helps to calculate the potential improvement of environmental impacts without compromising the economic return. Through the comparisons of those single eco-efficiency score, the policy recommendation can be formulated for sustainable and optimal input mix to produce a certain level of output with a minimum damage to environment.

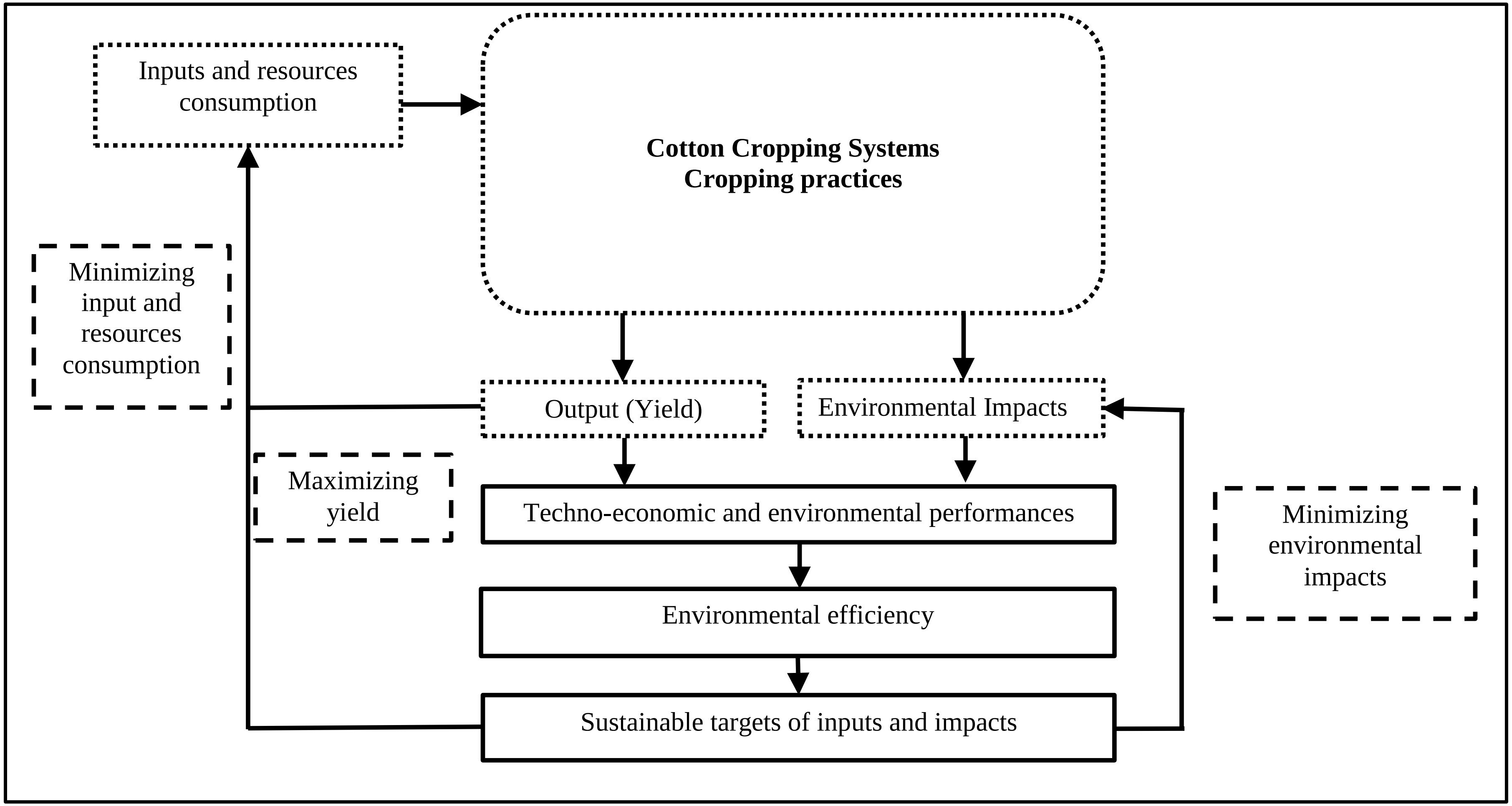


Figure 1.1 Conceptual framework of the research: dotted frames reflect facts and reality; solid lined frames refer to analysis and knowledge; dashed frames refer to objectives.

1.6 Scope and limitation of the study

This study evaluates the techno-economic and environmental performances of selected irrigated cotton cropping systems of Pakistan. The technical performance of the selected production systems was analyzed based on the productivities of different factors of productions. This approach helped to make it possible to analyze the scarcity of resources such as energy, water, land, labor and capital that can potentially be saved through the adoption of best management practices. Factors such as size of land holding, source and mode of irrigation, agronomic practices, processing and transportation of inputs have been considered as part of this study to assess the potential environmental impact of cotton production sub-systems. The input related impacts such as use of energy, water, pesticides, labor, and fertilizer and output related impacts such as global warming potential, eutrophication, acidification and eco-toxicity has been analyzed through life cycle assessment approach.

As the concept eco-efficiency encompass environmental and economic dimension of agriculture production systems therefore the assessment of potential environmental impact is not the only task of the present study but the technical and economic performance has been analyzed. The economic return has been analyzed based on the production cost, net income from cotton crop and thus the profitability of selected cotton production systems. The farming system has been evaluated consisting of the farm and it main inputs. The emission as a result of the application of the inputs has been considered as the part of the system. When seed cotton as a product leaves the farm, is no longer a part of the system as the processes beyond the farm gate are not considered in this study. The farm houses, farm roads, and the drainage networks, are not considered in this study.

However, the research has certain limitations. The first of which is this study primarily focused on the utilization and management of the material inputs whereas the techno-economic and environmental performances and the efficiencies of these domains are not solely dependent on management and inputs. To some extent, some other contextual factors such as soil properties and qualities and pest pressure and incidences also effects on the performances and efficiencies of cotton production systems. Some other institutional factors are also lacking in this study. Nevertheless, the findings that are materialized from the analysis of this study are useful for policy makers and planners. The second limitation is that farmers are cropping different varieties of cottons in their farm and possibly there are variations in the output.

1.7 Structure of the Dissertation

This dissertation has been arranged into eight interrelated chapters. The introduction chapter is followed by chapter 2 which is the reviews of literature related to cotton crop production, the economic and environmental performances of cotton crop. Chapter 3 describes the research design, the selection of the study area, data requirement, and various types of methodological approaches used in this study. Chapter 4 describes the technical and cost efficiency analysis of cotton crop production followed by the analysis of the contextual factors that influences these efficiencies domains. Chapter 5 describes the environmental performance of cotton crop. In Chapter 6, the direct emissions from the cotton crop have been modeled. Chapter 7 discusses the eco-efficiency analysis of selected irrigated cotton cropping systems. Finally in Chapter 8, based on results and discussions, conclusions have been drawn and some appropriate policy recommendations are provided.

Chapter 2

Review of Literature

2.1 Cotton production in Pakistan

Pakistan is the world fourth largest cotton producer after China, India and the USA with a 9.5 percent share of global cotton production. The area under cotton crop in Pakistan is about 2,820 thousand hectares for the year 2011-12 and the production was estimated at 11,819 bales with an average cotton lint yield of 731 kg/hectare (Agricultural Statistics of Pakistan, 2010-11). Most cotton growers of Pakistan are small land holders and many of these cotton growers are tenants. They are doing pesticide-based farming as the liberalization of generic pesticides imports increased the pesticides use many folds without enhancing the well-being of the farmers (Khan and Iqbal, 2005). Consequently adverse environmental impacts are being caused due to heavy use of pesticides and inefficient irrigation practices in the cotton production systems of Pakistan (Kooistra et al., 2006).

There are many factors affecting the production of cotton in Pakistan. Besides environmental issues, availability of quality seeds, irrigation water and use of fertilizers and pesticides are very important factors affecting cotton production. The size of land holding also affects the productivity as the small farms are less mechanized as compared to large farms which are more technology and resource oriented (Chaudhry and Khan, 2009). The observed variation in total production and area under cotton crop is due to changing market situation, the prices of inputs as well as the demand for alternative crop.

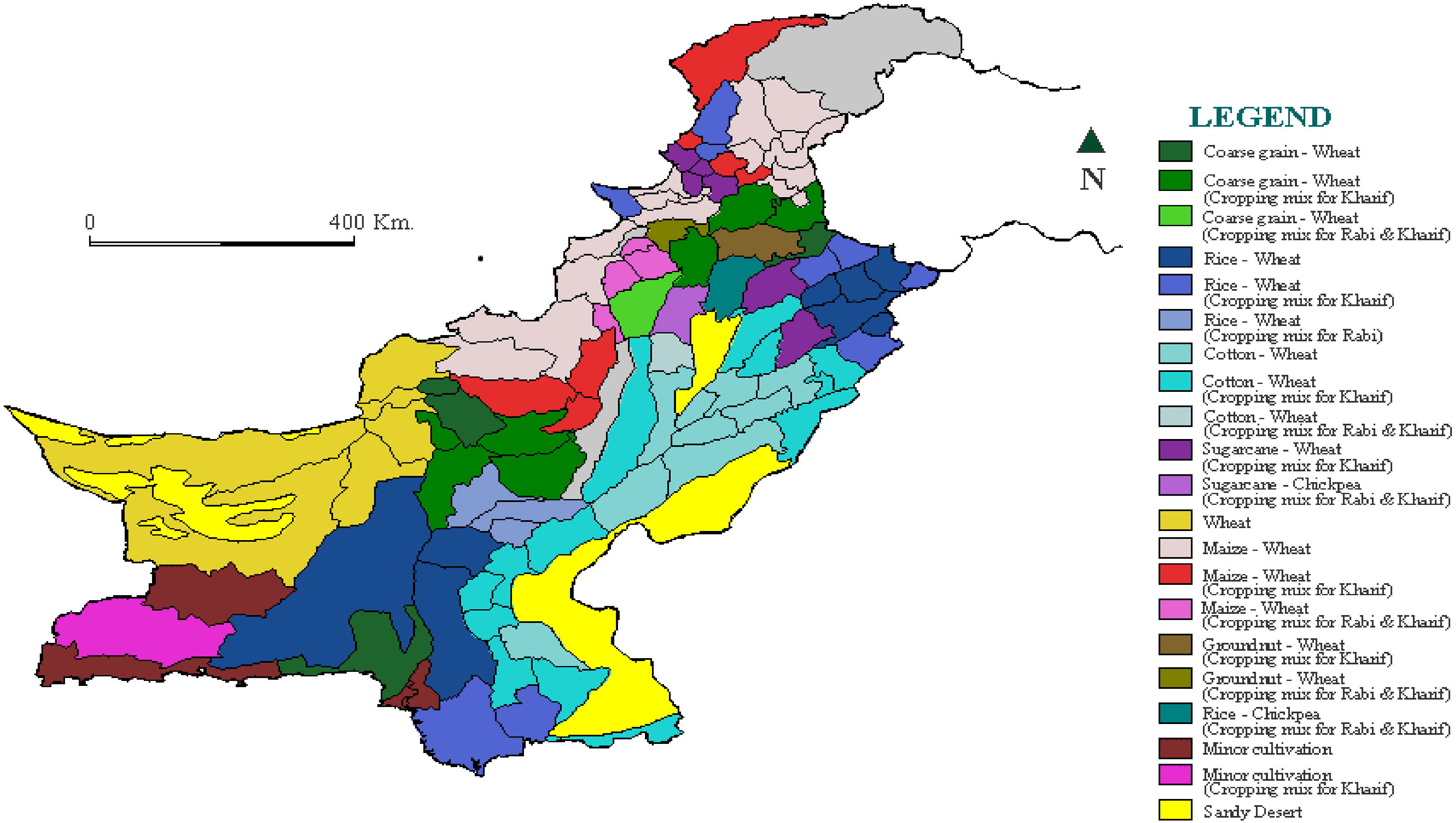
Since the inception of Pakistan in 1947 until 1960 agro-chemical use was almost negligible in the country. However with the passage of time especially in 1970 and onward the pressure to grow more was increased and as a consequence the chemical were used to control the increasing insect and pest attacks on cotton crop. Consumption of pesticides was 665 metric tonnes in 1980 (Khan et al, 2002) and reached 97,606 metric tonnes in 2007 (Agriculture Statistics of Pakistan, 2006-07).

There is a significant yield gap between the progressive and average farmers who are large in number. The total number of cotton farms in the country is 1,626,765 with total farm area of 3,201,206 hectare. The average farm size is about 2 hectares. Cotton farm by size and area is given in table number 2.1.

Table 2.1 Cotton farms by size and area

Farm Size (hectares)	**Percent of Farm**	**Percent of Area**	**Numbers of Farms**
Less than 2 hectare	49	18	797,505
2 to under 5 hectare	33	32	533,364
5 to under 10 hectare	12	21	193,952
10 to under 20 hectare	4	15	75,211
20 hectare and above	2	14	2,733

Source: Economic Survey of Pakistan. (2011-12)

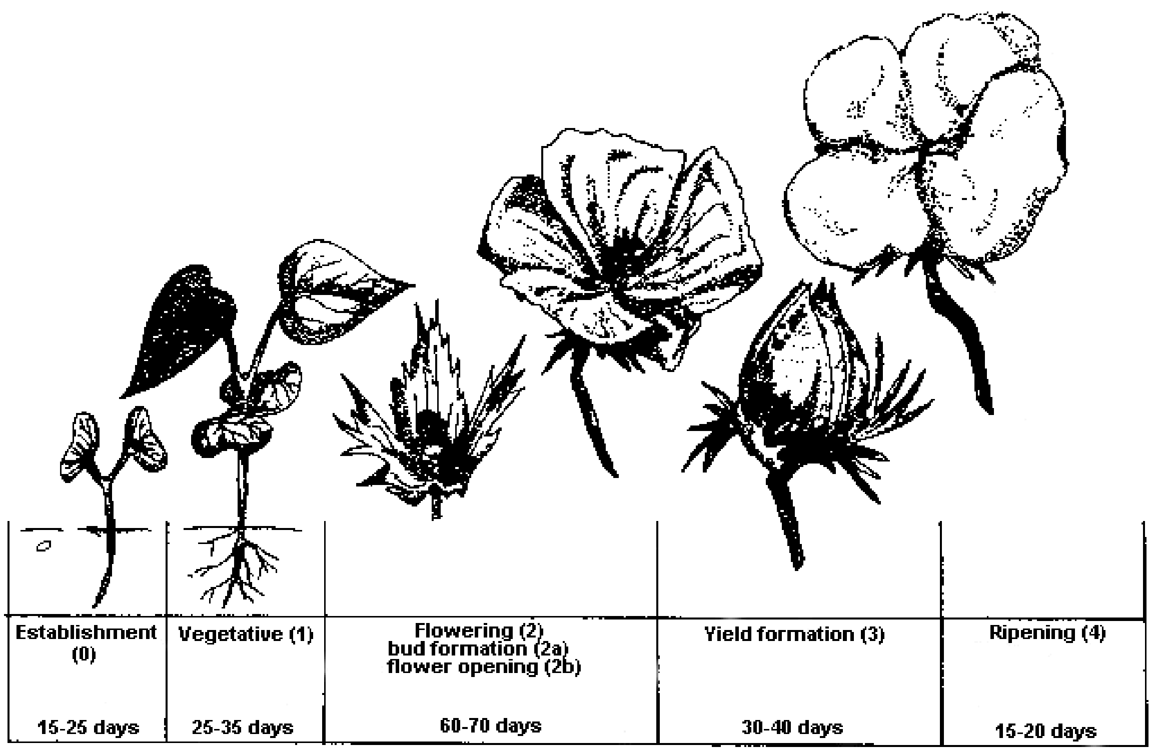


Source: PARC, (2000)

Figure 2.1 Cropping pattern of Pakistan

Cotton is a very draught sensitive crop, low temperature and the attack of different insects. The optimum temperature range for cotton cultivation is 18-30 degree Celsius with minimum 14 degree Celsius and maximum 40 degree Celsius. Cotton is very sensitive to high rainfall but at the same time it needs huge amount of irrigation water depending upon the climate and the length of the total growing period. Cotton crop nitrogen requirement is 100-180 kg per hectare, phosphorus 20-60 kg per hectare and potassium 50-80 kg per hectare. Enormous environmental impacts are being caused by intensive agro-chemical use and the inefficient irrigation systems (Kooistra et al., 2006).

The cotton growing area in Pakistan has the subtropical climatic characteristics and receives irregular rainfall with mean annual rainfall between 142-180 mm. Most of the rain is received during the monsoon period i.e. mid June to September with high intensity downpour. In Pakistan two types of crop season exists and these are named Kharif crops and Rabi crops. Kharif crops are referred to summer crops and are planted for autumn harvest. Rabi crops referred to winter crops and are planted for spring harvest. Cotton is a kharif crop and it is planted during the period of mid of May to mid of June. Most of the cotton crop in Pakistan is grown in the silty alluvial soil with low organic matter contents. Cotton is grown after wheat crop and flood irrigation is applied. First irrigation is applied in order to permit the primary tillage for weed control and soil loosening followed by further irrigation to increase the water contents in the soil profile. The surface soil is allowed to dry in order to do good tillage operation and seedbed is prepared (Nabi at el., 2001)



Source: FAO (2005)

Figure 2.2 Growth stages of cotton

Cotton is harvested in October to December, with peak harvesting season in November. After harvesting cotton crop mostly farmers grow wheat. The general cotton production practices is given is figure 2.3. Cultivation of cotton creates many negative environmental externalities.

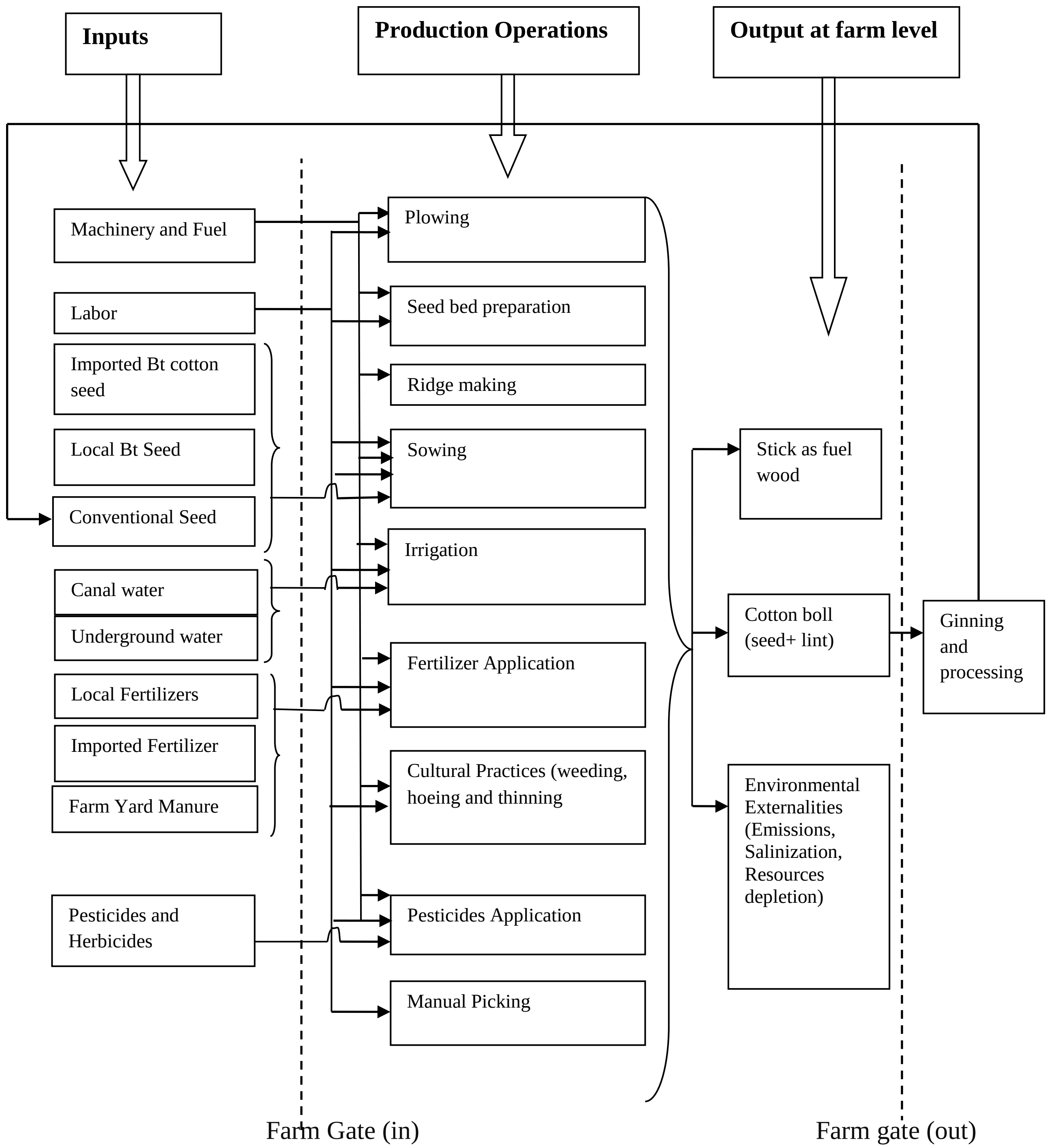


Figure 2.3 General flow diagram of cotton crop production

2.2 Cotton and irrigation

Worldwide about 53 percent of cotton field is irrigated and producing about 73 percent of the global cotton production (Soth et al., 1999). In most irrigation systems, cotton crop is irrigated through traditional techniques of flood and furrow irrigation. Cotton irrigation water requirement is partially fulfilled by surface water through gravitational flow from Rive Indus and its tributaries and partially by groundwater through pumping. There are huge losses of irrigation water due to evaporation, seepage and mismanagement. Also the cotton production involves in other environmental degradation such as eutrophication, salinization, pollution and water logging (Cherret, 2005).

In Pakistan the cotton crop water requirement is being supplemented by underground water and about 31 percent of all irrigation water is being drawn from groundwater causing a fall of water table (Soth et al., 1999). Environmentally the impact of extraction of underground water is twofold, the fresh water depletion and the use of energy to pump out the underground water. In addition it also affects the ecosystem quality if saline underground water is used for irrigation and ultimately it causes secondary salinization.

Flood and furrow irrigation are common modes of irrigation in cotton crop production. In flood irrigation system, the cotton is grown on the seedbed. In furrow irrigation system the cotton is planted on the ridges and water is supplied in small channels in between the ridges. These systems are considered cheap because the main cost incurred only in the leveling, making ridges and the pumping of irrigation water. Globally due to large number of flood and furrow irrigation methods in the production systems of cotton crop, the average irrigation efficiency is estimated as 40%. So 60% of the irrigation water is not being used by plants (Stockle, 2001). Therefore the optimization of the irrigation techniques and the estimation of cotton crop water requirement are necessary.

Generally cotton crop requires about 550-950 liter per square meter. The worldwide per hectare average yield of cotton crop is 1600 kg of raw cotton including both lint and seed. However the worldwide average per hectare yield of lint is 550 kg. In other words in order to 10,000 to 17,000 liter of water is required to produce one kilogram of cotton lint (Kooistra et al., 2006). According to (Soth et al., 1999) 53% of cotton is irrigated and the contribution to the total yield of irrigated cotton is about 73%.

2.3 Cotton and the environment

The farming systems have been intensified in many countries in order to produce more per unit area of land. The intensification of conventional agricultural systems (also known as green revolution) was primarily based on the increased use of high yielding varieties, chemical fertilizers, pesticides, irrigation water and energy per unit area of land, and it contributed substantially to increased agricultural production. At local, regional and global level only the ecologically based management strategies can reduce the off-site negative consequences and increase the sustainability in agricultural production (Matson et al., 1997).

2.3.1 Irrigation related environmental impacts of cotton crop

The environmental impacts related to irrigation water are not only the fresh water resource depletion and the fresh water ecosystem impacts as discussed by Milà i Canals et al. (2009). The irrational use of fresh water causes resources deprivation and biodiversity losses as well as water-logging and salinity problem. Assessment of the use of freshwater provides the way to a sustainable use of freshwater resources. Institute for European Environmental Policy (IEEP, 2005) stated that cotton production is creating adverse environmental impacts such as land degradation as a result of salinization and erosion, water depletion due to excessive use of underground and surface water, eutrophication of surface water, and wildlife contamination due to heavy pesticide use, human health effect due to direct intake or due to contamination of drinking water.

The virtual water content in the seed cotton (un-ginned picked cotton including seed and lint) is calculated based on water used during the entire period of crop growth to produce a certain amount of seed cotton. Chapagain et al. (2006) calculated the virtual water content of 15 largest cotton producing countries. They only considered that green virtual water (ratio of effective rainfall to cotton crop yield) and blue water (ratio of the volume of irrigation water to the cotton crop yield). They ignored the amount of water polluted by different practices during the crop growth. The virtual water content also varies with spatial variation of the production systems of cotton crop. The total amount of water required by crop depends upon the climatic condition and the type of soil it is grown.

The virtual water content of seed cotton of different countries provides a rough picture of the various production systems of cotton crops. The virtual content of seed cotton in Pakistan was calculated as 4914 m^3/ton. The virtual water content of seed cotton in China was calculated as 2018 m^3/ton, Argentina 7700 m^3/ton, India the highest amount as 8662 m^3/ton and in USA it was calculated as 2249 m^3/ton (Chapagain et al., 2006).

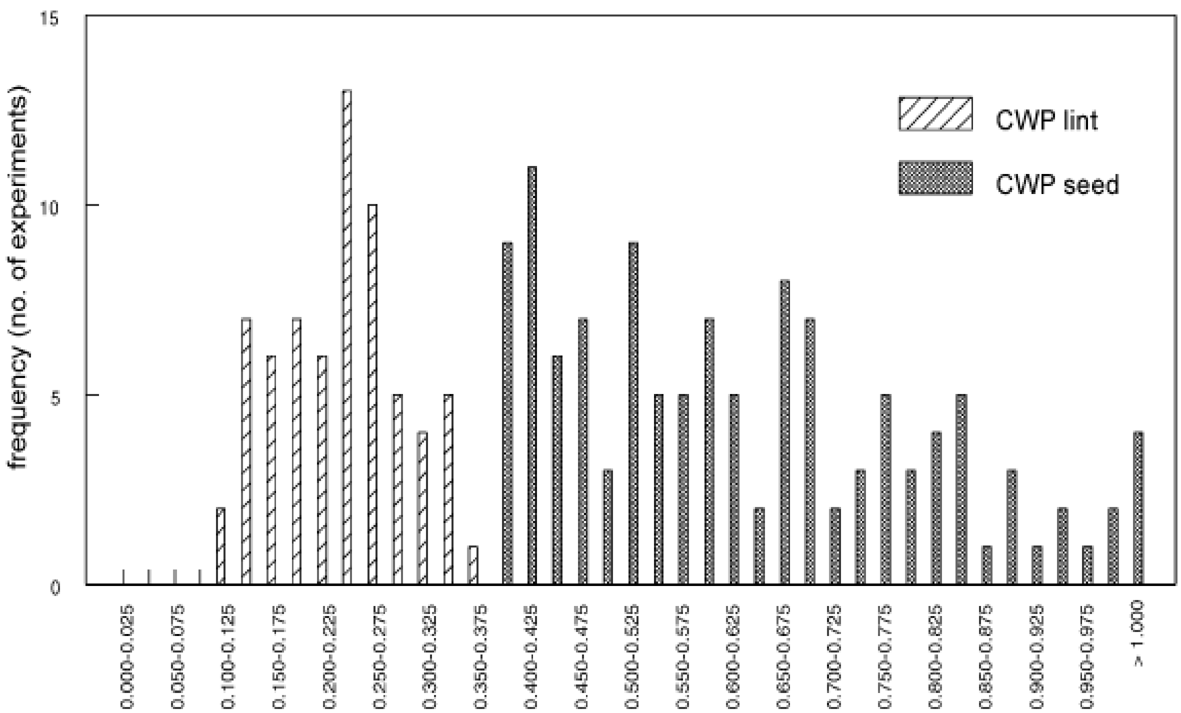
Chapagain and Orr (2009) introduced the methodology to calculate water withdrawal and subsequent evaporation from the field crop by using publically available CROPWAT model. The virtual water content is the ratio of water used in the crop production to the amount of crop produced and it spatially varies for different systems of the same crop (Chapagain and Orr, 2009). The water used in the production of a crop can be classified into two components, the evaporative water use and the non-evaporative water use (Milà i Canals et al., 2009; Chapagain and Orr, 2009). The evaporative use is further divided into two components i.e. green water and blue water. The non-evaporative used water is the polluted water due leaching of the fertilizers, pesticides and other chemicals (Chapagain and Orr., 2009).

Crop water productivity (CWP) ratio is calculated by dividing marketable produce of a crop to its actual water consumption through evapotranspiration. CWP of cotton has been analyzed by Zwart and Bastiaanssen (2004) which is shown in figure 2.4. It shows that cotton seed CWP ranges 0.41 - 0.95 kilogram m^{-3} and for cotton lint 0.14 – 0.33 kilogram m^{-3}. Soth et al. (1999) outlined different mechanisms and impacts of cotton crop production on freshwater ecosystem and biodiversity as shown in table 2.1.

Table 2.2 Major impact of cotton on freshwater ecosystems and freshwater biodiversity

Mechanism	Pollutant/Change	Impact	Cases
Run off from fields	Fertilizer Pesticides Sediments	Eutrophication and pollution Wildlife contamination	
Drainage	Saline drainage water Pesticide or fertilizer contaminated drainage water	Salinization of freshwater Pollution of freshwater	China, Egypt, Uzbekistan
Application of pesticides	Insecticides, fungicides, herbicides and defoliants Spray drift (e.g. aerial application) Leakage of equipment	Wildlife contamination Contamination of adjacent wetlands, surface and ground water Contamination of surface and ground water	
Water withdrawal for irrigation	Use of ground water Use of surface water	Change of water table or depletion of ground water Degradation of wetlands and lakes	New South Wales, Australia Aral Sea, Yellow River Valley
Extensive irrigation	Water logging	Raising water tables and salinization of soil surface	Australia, Indus River Valley, Uzbekistan, Pakistan
Dam construction for irrigation	Regulated water flow	Habitat destruction, change of water table and change of water flow	
Land reclamation	Change of vegetation	Habitat destruction	

Source: Soth et al. (1999)



Crop water productivity (kg m^{-3}) of seed and lint

(Source: Zwart and Bastiaanssen (2004))

Figure 2.4 Frequency of crop water productivity (CWP) per unit water depletion for cotton lint and cotton seed

2.3.2 Energy inputs in cotton crop production

Depending on the sources of energy, different forms of energy are used in cotton crop production systems. For accounting purposes these energy forms are classified into direct and indirect energy uses (Chamsing et al., 2006). Direct energy is the amount of energy that is consumed directly at farm level in order to perform different farm activities such as seedbed preparation, sowing, cultural practices, irrigation and picking. The indirect energy is the amount of energy used in manufacturing and transportation phases of agro-chemicals and machinery. Energy use can also be classified into renewable energy (human labor, seed and farmyard manure) and non-renewable energy (fossil fuel, electricity and machinery). Similarly, the energy can be classified into commercial energy i.e. fossil fuel, electricity, agro-chemicals and seed and non-commercial energy i.e. human, animal and farmyard manure (Singh et al., 2007).

2.3.3 Use of fertilizer and its environmental impact

Adequate nutrient is necessary for crop growth. The synthetic fertilizers that are used in cotton crop are typically the combination of nitrogen (N), phosphorous (P) and potassium (K). Livestock manure is also used as a key source of nitrogen in organic farming. Legume crops may also be cultivated in rotation with cotton crop in order to maintain nitrogen fertility in the soil through symbiotic nitrogen fixing. Since green revolution use of synthetic fertilizers increased due to its increased availability and as a consequence legumes cultivation has been decreased. The Central Cotton Research Institute (CCRI) Multan in Pakistan recommended 59 kilogram of phosphorous fertilizer per hectare at the time sowing of cotton. At the time of first and second irrigation 27.17 and 59 kilogram of nitrogen per hectare respectively is recommended. The recommended dose at the time of ridging/ earthing up is 59 kilogram of nitrogen per hectare.

There are many negative environmental impacts of using fertilizers. Heavy use of nitrogen fertilizer can create the problem of acidification and also off site negative environmental impacts. The plants utilize fully nitrogen if applied at proper time. If not or if overused then it will be unused, denitrified and leached down into groundwater or washed into surface water that can be a potential harm for environment especially water pollution. Nitrate moves to the surface water and accelerate eutrophication. Phosphorus attached with sediments and also contributes to eutrophication if the soil is eroded. Eutrophication depletes the available oxygen and reduces the population of aquatic plants and animals (Uri, 1998).

Chapagain et al. (2006) reported that 53,672 ton of nitrogen leached to the water bodies annually in Pakistan and 1,040 m^3 of water is required to dilute one ton of nitrogen. Besides the aquatic eutrophication and acidification potential, the emission of CO_2, N_2O, NH_3, and NO_3 are resulted during the production, transportation and after application of nitrogen fertilizers. N_2O is a potential GHG and it negatively affects the environment. The nitrogen fertilizer application is a potential source of greenhouse gases emissions. Due to nitrification of the organic matter from plants and animals and chemical fertilizer NO_2 and NO_3 are produced. The nitrates either leached down or contaminate the groundwater or due to denitrification it is converted to nitrous oxides and emitted into air. Due to run off the nitrogen fertilizer can be washed down to the surface water and cause the eutrophication. The rate of emission increases with the increase of the application the nitrogen fertilizers and it also deplete the energy resources therefore the use of nitrogen fertilizer is responsible for global warming potential as well (Brentrup et al., 2005). The mining of phosphorus and potassium contributes to water and air pollution as well as the landscape change.

2.3.4 Pesticide use in cotton production and its environmental impacts

Wide diversity and large quantities of chemicals are used in cotton cropping. Pest outbreaks in cotton crop cause qualitative (fiber quality deterioration) and quantitative (yield reduction) damages to the crop. Farmers use pesticides to control insect pest attacks. In the mechanical picking of cotton, defoliants are used prior to harvest. The application mode, frequency, quantity per application and the timing of these chemicals during the crop growth period affect the environment differently. Farmers are usually more concerned about the pesticide cost incurred to get the desirable cotton output, and less concern about the undesirable externalities of the use of pesticides (Khan et al., 2002; Wilson and Tisdell, 2001).

There are three groups of insects to which cotton plant is vulnerable. These groups are the mealy bug, sucking insects and bollworms. Jassids, Aphids and Thrips feed on sap of cotton crop. White fly is another harmful insect and it is a cotton leaf curl virus transmitter. The attack of Thrips on cotton can be controlled through seed treatment with chemicals at the time of sowing. However the Aphids and Whiteflies are commonly controlled by spray of insecticides at later stage. The bollworms are also controlled by using of spray. The farmers in the cotton growing areas of Pakistan apply pesticides with short intervals. The farmers use 8-13 sprays per season, which is against the recommendation. The commonly used pesticides against whitefly and bollworm are monocrotophos, cypermethrin, methamidophos, and dimethoate. Due to exclusive use of pesticides the whitefly and bollworm developed resistance to most of the conventional insecticides on one side and due to heavy use of insecticides the natural enemies of these insects have been reduced (Tariq at el., 2007).

Wide spread use of pesticides in Pakistan control pest attack but it is also causing the environmental problems. Due to pesticide use the underground water in cotton growing regions of Pakistan is under continuous process of contamination. Due to overuse and misuse of pesticides in the cotton area, field workers and cotton pickers are under risk (Tariq et al., 2007).

The genetically modified Bt cotton have only the resistance to bollworm but it is susceptible to other insects. However fewer insecticides are used in case of Bt cotton then conventional cotton crop and as a consequence there is less toxic effect from Bt cotton. Different studies have been done on the assessment of the environmental and economic performance of the adaption of Bt cotton. Morse et al. (2006) concluded that the adoption of Bt cotton have environmental as well as economic benefits because of lesser use of insecticides and higher yield of Bt cotton. Wossink and Denaux. (2006) found that the adoption of genetically modified Bt cotton helps in the reduction of potential environmental impacts due to lesser use of chemical insecticides but the producers are not benefiting because the avoided costs from reduced insecticide use are less than the cost of Bt seed. Subramanian & Qaim, (2008) reported that Bt technology can potentially lead to different impacts by farm size due to financial and human capital constraints even if the technology is neutral to farm scale. They also recommended that the analysis of interaction of genetically modified crop and the ecosystem is necessary. Ali and Abdulai (2010) showed that adoption of Bt cotton increases the yield, reduces the pesticide application, increases the household income and thus reduces poverty. They also showed that the productivity of Bt cotton for small farmers is higher than for medium and large farmers.

As environmental degradation, climate change, and increasing demand of food and fiber are the growing concerns of the present era, increasing the productivity of agricultural land and minimizing the environmental impact are big challenges for future agriculture. In order to overcome these problems, eco-intensification or eco-functional intensification is one of the best possible options. It stands for “producing more agricultural output without compromising the quality of the environment, of foods/fiber, the quality of life of farmers and welfare of farm animals" (Niggli et al., 2008). Eco-intensification is possible only with the efficient uses of natural resources keeping in view the health of the surrounding environment, best management practices, enhancing the diversity of crop and livestock. Eco-intensification intensifies the beneficial effect of ecosystem function and improves the self-regulatory mechanism through beneficial effects on biodiversity and soil fertility (Niggli et al., 2008).

2.3.5 Concluding remarks

From the analysis of the first two sections it has been established that cotton is a resource and input consuming crop. It interacts with the environment with many potential impacts due to heavy use of resources such as water and energy and other material inputs such as fertilizers and pesticides. A comprehensive analysis of cotton productions systems, it performances and efficiencies is demanding and it is necessary to include all inputs, resources, then possible impacts and outputs.

2.4 Techno economic performances and efficiency

The estimation of techno economic performance is very important in developing context with limited resources. It can help estimate the possible increase of production in agriculture sector with more efficient use of inputs and resources.

2.4.1 Concept, definition, indicators

Techno economic performances and efficiency of cotton may be assessed with indicators of productivities of different inputs. An input's productivity is an absolute term and refers to the amount of output that can be produced as per unit of that given output. It may be quantified into respective physical units and monetary units for comparative purposes. Selected productivity and techno economic indicators are shown in table 2.3. These indicators are calculated based on primary data of the cropping systems, management sequences, input cost and production factor analysis, yield and farm gate price of output.

Indicators are needed to assess the quantity of the different inputs used to produce raw cotton in a given area and to assess the potential environmental impacts of crop production. Indicators are useful to rationalize the water, agrochemicals and mechanical use and thus help to achieve the optimal environmental level (Khan et al., 2009) in order to select the best possible practice. Crop production systems need energy in each phase of production whether in the form of direct or of embodied energy (Mushtaq et al., 2009). Energy consumption directly related to the advancement of the technology and the level of the production systems (Ozkan et al., 2004).

Table 2.3 Techno economic indicators of cotton production

Indicators	Units	Definition
Land productivity	Kg/hectare	$\frac{Cotton\ production\ (kg)}{Area\ under\ cotton\ crop\ (ha)}$
Energy productivity	Kg/MJ	$\frac{Cotton\ production\ (kg/ha)}{Energy\ input\ (MJ/ha)}$
Fertilizer Productivity	Kg/nutrients	$\frac{Cotton\ production\ (kg/ha)}{N, P, K\ units\ (kg/ha)}$
Water productivity	Kg/m^3	$\frac{Cotton\ production\ (kg/ha)}{Water\ applied\ (\mathrm{m}^3/ha)}$
Pesticide productivity	Kg/gram of active matter	$\frac{Cotton\ production\ (kg/ha)}{Active\ matter\ (g/ha)}$
Labor productivity	man hour	$\frac{Cotton\ production\ (kg/ha)}{Labour\ hour\ (man\ hours/ha)}$
Benefit cost ratio	Ratio	$\frac{Total\ benefit\ (\$)/kg}{Total\ cost\ (\$)/kg}$
Gross margin per hectare	$/ha	$\frac{Total\ benefit - Total\ cost}{ha}$

Source: Mushtaq et al. (2009)

2.4.2 Approaches and tools for efficiency analysis

Efficiency is a relative term and is used to compare the actual ration of output to input with the optimum level of output to input. The measurement of the efficiency of a system was introduced by Farrell (1957) by dividing the efficiency into technical efficiency and allocative efficiency. Technical efficiency is the maximum possible output with the given set of inputs. Technical efficiency is linked with the technology or the inputs of farming and it mainly deals with production of the farm without considering the prices of inputs and output and therefore it is also called agronomic efficiency. On the other hand the allocative efficiency is the price adjustment of the inputs and output after the production technology is selected. After the farm attains technical and allocative efficiency then it fulfills the condition of economic efficiency (Dahal, 1996; Javed, 2009).

There are two possible approaches to analyze the efficiency of a firm: the parametric approach and non-parametric approach. The parametric approach can be further classified into deterministic and stochastic frontier. Deterministic frontier is the one where all observation lies on or below the frontier and if the observation lies above the frontier due to random error then it is called stochastic frontier.

The non-parametric approach is commonly known as data envelopment analysis (DEA) models developed by Charnes *et al*. (1978) which uses the data of input and output to construct best practice production frontier over the data points. The frontier surface is constructed through a sequence of linear programming problems (one for each unit known as data management units (DMUs). The efficiency of each DMU is measured relative to the efficiency of all other DMUs. DEA was developed by Charnes et al., (1978). DEA can either be input oriented or output oriented depending upon the orientation used. DEA determine the maximum possible proportional reduction in input without disturbing the output level or it helps to find out the maximum amount of output without any increase in input levels depending upon the objective function.

The main advantage of the parametric method known as Stochastic Frontier Production Function (SFPF) is it permits to test the hypothesis concerning the goodness of fit of the model but it needs the specification of the technology that is difficult for some cases. On the other hand the advantage of non – parametric method (DEA) is that it does not need any specification of any functional farm of the technology but it does not estimate the parameters of the model and thus restrictive to test the hypothesis (Ajibefun, 2008). It can also readily incorporate multiple input and output. It does not need any assumption of the functional farm to specify the relationship between input and output and about the distribution of the underlying data.

Ajibefun, (2008) described, that estimating of technical efficiency is very important because it is a success indicator of the performance measures through which the unit of production can be evaluated and it also measures the causes of inefficiencies and eliminates it. Identification of the sources of inefficiencies is necessary in order to improve the performance of the system. Both of the parametric and non-parametric method estimate inefficiencies through a common concept of frontier meaning that the efficient production units are those operate at production frontier. The units that operate below the production frontier are inefficient production units. Thus the level of inefficiency is measured based in the deviation from the frontier. Charnes et al. (1978) developed constant return to scale model and is known as CCR model. The constant return to scale is possible if all the firms operate at optimal level but it is not possible in agriculture. Later on Bankers at el. (1984) modified constant return to scale to variable return to scale model and this model is known as BCC model. The variable return to scale (VRS) slack based DEA model was developed by Pastor et al. (1999); Cooper et al. (2007) and are used by different authors in their respective studies.

2.4.3 Approaching efficiency with DEA, cases on cotton

The basic idea of calculating the relative efficiency of a set of DMUs is to construct a piecewise frontier; all of the efficient DMUs lie on the frontier, and the DMUs below the frontier are considered to be inefficient. DMUs efficiency score range between 1 (full efficiency) and 0 (full inefficiency).

The production frontier symbolises the minimum input requirement to produce a certain amount of output. A cost frontier describes the minimum cost incurred to produce a certain amount of output (Nguyen et al. 2012), and the environmental efficiency represents the minimum production environmental impacts or undesirable outputs without compromising the given level of desirable output.

There are three approaches to efficiency with DEA. The first aims at seeking a reduction of the amount of input for producing a constant output (input-oriented DEA); the second aims at seeking an increase of the output while maintaining the level of input (output-oriented DEA); the third is a mixed approach of reducing input while increasing output. Regarding agricultural production, farmers only control the amount of inputs they use; therefore, the input-oriented efficiency model was selected for technical and cost efficiency analysis.

It is considered that the transgenic crop requires fewer amounts of pesticides then the conventional cotton production systems. The use of partial efficiency can give a spurious result as it is not easy to identify the factor that affects the measure (Wossink and Denaux, 2006). Wossin and Denux (2006) assessed technical, environmental and cost efficiency of pesticides use in conventional and transgenic cotton production by using data envelopment analysis (DEA). The decision making units were compared by calculating the point of inefficiencies i.e. the points below the frontier of different decision making units through input oriented approach with an aim to reduce the pollution from pesticides. Nassiri and Sing (2009) used output oriented DEA method to assess category wise and zone wise energy efficiency in paddy crop.

2.5 Environmental performance, efficiency and impacts

There are different tools that can be used to evaluate the environmental profile of cotton. The choice of best method depends upon the feasibility, scientific relevance and the orientation used. Each method relies on some indicators serving as criteria to evaluate if the objectives can be attained. These indicators account for local, regional or global impacts. The product related tools that are mainly used for the assessment of its environmental profile are; Life Cycle Assessment (LCA), Material Input per Service analysis (MIPS), Material Flow Analysis (MFA), Substance flow Analysis (SFA) and Cumulative Energy Flow Analysis. Beside that some analytical tools for eco-design can also be used. It requires some quantitative tool like LCA, matrices and checklist. The project related methods that can be used in cotton is Environmental Risk Assessment (ERA). Environmental Extended Input-Output (EEIO) Analysis and Strategic Environmental Assessment (SEA) are the methods that are used for a sector or country level.

Payraudeau and van der Werf (2005) reviewed some possible methods/tools to assess the environmental impact of farming systems and they discussed the suitability of each method in different contexts. Keeping in view the processes involved and the material and energy flow in crop production systems, following are some major methods/tools that can be used for the assessment of environmental profile of cotton.

2.5.1 Comparison of impact assessment methods

To identify and assess the environmental impacts and also find out the opportunities to reduce the environmental impact of a project, process, product and service and the risk associated with it, LCA, EIA and ERA are some suitable tools that are possibly used for the detailed environmental impact assessment of cotton production.

EIA is a procedure that is used to evaluate the positive and negative environmental impacts of a future project and its spatial boundary is limited only to the boundary of the project. In most EIA the upstream and downstream effects are not considered. EIA is considered a point source oriented environmental evaluation method and takes into account the time related aspect of a specific geographic location (Tukker, 2000). The impact parameters that are used in EIA depend on the specific plan or project. The main limitation of EIA is its inability to address the global and regional impacts throughout the life cycle of a process and this weakness is complemented through incorporation of LCA. "EIA can be complementary to LCA, since it provides further and more detailed information about the analyzed object" (Manuilova et al., 2009). In LCA all the upstream and downstream activities, their relevant effects and possible improvements throughout the life cycle of a product are considered, quantified and compared (Manuilova et al., 2009). LCA is used with its emphasis on a time and location-independent assessment of potential impacts in relation to an entire production system and is a complement to EIA (Tukker, 2000).

Environmental risk assessment (ERA) tries to evaluate the risk toward which human health and/or the natural ecosystem are vulnerable due to human intervention or due to some natural phenomenon. The term risk has different meanings in different contexts. Brookes. (2001) defined risk "is a combination of the probability or frequency of the occurrence of a particular hazard and the magnitude of the adverse effects or harm arising to the quality of human health or the environment". Environmental risk assessment is a method that is used in gathering the available information about the environmental risk and making some judgment about it. It is used to balance the environmental cost and environmental benefit. Risk assessment tool is used for occupational safety and setting priorities for the allocation of resources (Brookes, 2001).

ERA can systematically identify the potential hazard, the route by which hazard occur and estimate the chances or probability of occurrence followed by the potential consequences on the human health and natural ecosystem due to the exposure to the hazard. Both qualitative and quantitative approaches are used to estimate the probabilities and consequences of the potential risk. Mitigation measures are identified for potential risks. The priorities can be made to manage the risk according to the rating of the risk.

Environmental risk assessment method can be used in the farming systems and to analyze the environmental profile of agricultural products. The risk can be associated with the farming practices and pollutant emissions. It generally deals with the single environmental aspect such as risk of nitrate leaching, or flow of phosphorus or pesticides (Payraudeau and van der Werf, 2005).

Jeswani et al. (2010) explained the differences between LCA and ERA. Both LCA and ERA are analytical tool used assess the environmental impact of a process and to support the decision making process. ERA is designed to assess the hazards for short term perspectives and it is also location specific while LCA assess the impact for long term perspectives at local, regional and global level. LCA compare the alternatives and assesses their relative impact of each impact category considered. Functional unit is very important feature of LCA used for relative assessment of a process. ERA assess the risk of a specific site and especially deals with the emission related to the chemicals. The reference value in ERA is based on the notion of an "acceptable risk" define by a threshold value while LCA is based on the "less is better".

ERA focus on specific harmful endpoint impacts of a product, process or events. In contrast LCA focus midpoint indicators as well. ERA provides the information regarding the timing of the impact but it is impossible with LCA. Beside that the absolute magnitude of a product or activity is very important in ERA. Both the tools are important at their specific places and cannot substitute each other. Their role in the total environmental effort is complementary. For the relative priority setting LCA and the absolute priority setting ERA is suitable (Olsan, 2001). ERA is useful to provide the data for toxicity that is an impact category used in LCA.

2.6 Insight into Life Cycle Assessment

Keeping in view the objectives of the proposed research, Life Cycle Assessment (LCA) enables to study the whole product system and helps us to avoid the sub optimization. Sub optimization can occur if only few and site specific processes will be focused. It also enables us to study different alternatives in the production system and make comparison and to select the best possible option among different (Baumann & Tillman., 2004). LCA is a comprehensive tool and helps to assess the potential sources of pollution, its local, regional and global impacts and the extent of scarce resources utilization such as water and energy in production systems of cotton crop. The overall environmental impact of a farming region is often assumed is equal to the sum of the impact of each farm. It is not always true because different systems utilize different quantities of resources and adversely affect the environment differently.

Life Cycle Assessment (LCA) is a quantitative tool that is used to evaluate the environmental impact of the production processes, the use and the disposal of a product. LCA helps to assess the emissions, resource utilization and its impact on the surrounding environment, either during the whole course of life of a product (from cradle to grave) or at the production stage (from cradle to gate), into small number of indicators. It helps to calculate the potential impacts of a product at local, regional or global level. LCA is process oriented method with a predesigned system boundary. LCA together with some other approach provides much more reliable and comprehensive information to the policy makers, producers and consumers to adopt sustainable production processes. It helps to compare the alternative products, production processes and the services of a product. It also helps to identify the individual processes which are more responsible for environmental load in the life cycle of a product and help to find out the way of improvement (Roy et al., 2009).

Many non-point sources of pollution and toxicity risks are associated with cotton production and it may hamper the export of cotton in future and will also affect the ecosystem. The application of LCA is also helpful in the area of marketing of cotton product as LCA based communication tool helps to declare the environmental characteristics of a product and thus it promote the product export. There are many concerns about the environmental impacts of production systems especially in developed countries. LCA is a more comprehensive tool, compare the alternatives, and deals the assessment of potential environmental impacts in large spatial and temporal scales. In order to assess the impact in long term perspective and make the strategies accordingly, LCA deals the best as it takes into account all the relevant effects and an honest comparison is possible.

Life cycle assessment (LCA) is an approach to integrate and assess the environmental impact of different steps involved in the production systems and to find out the hotspots of the environmental load of production (Mishima et al., 2005). The environmental impact is taking place at any time and at any place during the life cycle of a product. The criteria of the impact assessment of a product include all steps from the extraction of the resources, production processes and materials, distribution of the product, its use and the disposal of the product.

LCA evaluates all the interdependent stages of a product's life and it enables to estimate the environmental impacts resulting from all the activities involved and all the materials used throughout a product life cycle. LCA involves for the compiling of the energy and material inputs and the undesirable environmental output. It evaluates the potential environmental impact associated with the specific inputs and releases. Based on that potential environmental impact it help the decision makers to make alternative rational decisions (USEPA, 2006). Partial LCA is the assessment of only a compartment of the whole production chain.

The LCA methodology has four main stages which are: "goal and scope definition, inventory analysis, impact assessment and interpretation of result" (USEPA, 2006). These four steps are explained as under:

2.6.1 Goal and scope definition

The goal definition of LCA defines the product, processes or activities involved in the production system. It identify the system boundaries in which the potential environmental impacts to be reviewed and assessed. The goal and scope definition of LCA defines the context of the study, its depth and breadth and also the functional unit.

At the time of goal definition it is necessary to define the possible alternatives available for comparison purpose of a specific product, the product design and processes involved in it. Based on the defined goal, the systems boundaries are defined while considering the processes involved in it. Functional unit is necessary to define at the time of goal definition as on the basis of functional unit the comparison can be made.

During the scope definition, the categories of environmental impacts should be considered. The impact categories that are commonly used in the life cycle assessment are global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and resources depletion. Data inventory is developed based on the impact categories considered in the study. There are two main types of LCA, the "accounting type" that answer which environmental impacts are associated with some specific product and the "change type LCA" assess the environmental impacts of different courses of action. The definition of system boundary is necessary and cut off criteria is also necessary to define at the time of scope definition. Cut off criteria is considered to find out the inclusion or exclusion of processes inputs or outputs of a product analysis.

Generally the industrial processes are multifunctional and it is common that the system under study may provide more functions than the one investigated. In some industrial processes the recycle intermediate or discarded products are used as a raw material. Therefore an appropriate decision should be taken to allocate the environmental impacts to those multiple functions of the systems. To solve the problem of allocation there are three possible options: 1) avoiding allocation either by dividing multifunctional processes into two or more monofunctional subprocesses or the expansion of the product system by to include additional functions related to co-products 2) the partitioning of the environmental load at system's different functions based on the physical relationship and 3) allocation made according to the economic values of products (Guinée, 2002).

2.6.2 Life cycle inventory analysis

Inventory analysis means compiling, identifying and quantifying the activities and usage of energy, water and materials and the environmental releases e.g. air emission, solid disposal, waste discharges to water from the system being studied and evaluated. It is a critical stage and careful consideration is needed to quantifying the raw data of material inputs in the system and releases from the system. The flowchart for the flow of input and the output of material and energy is constructed in this stage. The inventory analysis in life cycle assessment is a cumulative and iterative process (Bauman and Tillma, 2004).

All the numerical data of all inputs and outputs of the modeled activities are required. The inputs include all materials and energy used including land use, in the modeled process. The output consists of the target product as well as the undesirable output into air, soil and water.

In order to support the allocation process some data is required such as the relative prices of the products. When several alternate allocations seem possible then the allocation can be avoided by increased level of data or by expending the system. Allocation can be based on the physical relationship of the inputs and the products. The transportation of the inputs, mode of transportation, distance and the energy used in the transportation of inputs and outputs are required depending upon the system boundary. Depending upon the scope of the study the upstream data, the process data and the downstream data are required for the inventory analysis.

2.6.3 Life cycle impact assessment

The aim of the life cycle impact assessment (LCIA) phase is to describe the environmental consequences of a product, process or a service. Different environmental consequences are analyzed based on the result of life cycle inventory. According to ISO 14042 LCIA standard, there are different phases of life cycle impact assessment. It starts from the identification and selection of the impact categories. These impact categories are divided into different sub categories based on its impact on the resources (energy, material, water and land), on human health due to toxicological effect and on the ecosystem (global warming potential, acidification, eutrophication, ecotoxicological impacts, impact on biodiversity (Bauman and Tillman, 2004).

From the LCI result, parameters are assigned into the respective impact category in the classification phase of LCIA. After classification phase the characterization of the environmental impact is performed. It is a quantitative step and in this step the environmental impact is calculated as per impact category by using characterization factors of each emission. In order to better understand the magnitude of the environmental impact of the system under study the normalization is performed in which the characterization results are related to the magnitude of each impact category caused by the system under study. The impacts categories are grouped according to their impact such local, regional and global impacts as per characterization results followed by weighting. In the weighting phase of the LCIA, the relative importance of different impact categories are expresses through relative weights.

In order to analyze the data quality and to better understand the significance of an impact the uncertainty and sensitivity analysis are performed. Both of these techniques are used to identify the most polluting activity in the life cycle of the product.

There are different impact categories that can be considered and analyzed in the life cycle impact assessment stage. These impact categories are either input related or output related. The input related categories are the abiotic resources depletion, loss of biodiversity and land use. Output related categories are global warming potential, ozone layer depletion, ecotoxicity, acidification, Eutrophication, photo-oxidant formation, odor, noise, radiation, casualties.

2.6.4 Interpretation

This stage of LCA is important and in this stage the interpretation of the results obtained from inventory analysis are performed in the context of goal and scope definition. It helps to develop subsequent strategies and better understanding in the process improvement. Different approaches used to analyze the result obtained from the life cycle of a product or processes are presented by Baumann and Tillman (2004).

Dominance analysis is used to investigate that which part of the life cycle gives the greatest environmental impact. It can be performed by analyzing the emission of each activity in the life cycle of a product. The dominance analysis is also possible to be performed for different stages in the life cycle of a product such a transportation, production and waste management. Contribution analysis is another approach similar to the dominance analysis used to identify the contribution of each environmental load contributes the most to the total environmental impact.

Break-even analysis is an important approach used to investigate the trade-offs options of environmental impacts. Decision makers analysis can also be performed to identify the extent of the environmental impact is under the control of the decision makers. The uncertainty analysis and sensitivity analysis are the tool use to assess the robustness of the result.

SimaPro is one of the life cycle assessment software which helps to analyze different categories of environmental impacts of a product during its entire life cycle. Based on LCA methodological approach, SimaPro calculates the results through characterization. Normalization and weighting can also be performed with the help of Simapro. A huge amount of data and knowledge about the environmental impacts of different processes are built-in into the program and database, which enable the environmental practitioners to analyze the environmental profile of a certain product. Many studies have been done on LCA of different products and SimaPro was used to assess the environmental impact indicators of those products. With the help SimaPro the damage path from the inventory and the environmental impacts hotspots of products can also be analyzed. There are different impacts categories used to assess the environmental impacts of a certain product.

2.7 Existing research on cotton LCA and other crop

2.7.1 LCA existing research on cotton

Cotton crop is known for large amounts of agrochemical applications and huge amount of freshwater water consumption. Different studies have been conducted to assess the partial environmental impact of cotton crop production with a main focus on water consumption. Matlock et al. (2008) performed the life cycle assessment of global cotton production with main objective to determine the energy required to produce one tone of raw cotton and compared the mechanized and non-mechanized farming systems. Pfister et al. (2009) analyzed the irrigation requirements, yield and environmental impact from water consumption of cotton production of different nations through LCA approach. A wide range inputs and practices are used in global cotton production systems and are responsible of different environmental impacts, have been discussed by Koositra et al. (2006) through comparison of conventional cotton farming, organic farming and the integrated pest management (IMP) systems and Cherrett et al. (2005) compared the ecological footprints of cotton, hemp and polyester. Steinberger et al. (2009) analyzed the life cycle inventory of global textile chain. The results of some of these studies shown in table 2.4 and mostly their results are limited to global level of specific impact categories such as water use and energy use and these studies have broadly focused the input use and the environmental impacts of cotton production at global or national level. No any research was found for a comprehensive life cycle assessment of cotton at field level considering the real farmer practices.

Table 2.4 Summarization of existing research on cotton

No.	Researchers	Detail
1	Cherrett et al. (2005)	Analyzed and compared the following indicators: - Energy use of organic cotton (11,711 MJ/tonne) and conventional cotton (25,591 MJ/tonne) fiber production in USA - CO2 emissions (2.35-5.88 kg of CO_2 per ton) of cotton fiber. - Water requirement between 763 and 915 m^3 of water (rainfall and/or irrigation) per growing season.
2	Koositra et al. (2006)	Reported water use of 550-950 liter per squar meter
4	Pfister et al. (2009)	Assessed water requirement of cotton textile (9.88 m^3/kg)
	Ridoutt and Pfister (2009)	Reported water requirement cotton T-shirt (2700 l/shirt
	Chapagain et al. (2005)	Described a wide range of water requirement 46 m^3/t in Brazil and 5602 m^3 / t in Turkmenistan

2.7.2 LCA existing research on other crops

LCA methodological approach has been used by Mishima et al. (2005) to study environmental impacts of paddy rice farming with livestock production. They compared different farming methods and those are "conventional farming, the standard application of chemical fertilizers and manure and low farming systems with low application of chemical fertilizers with forage production". They compared the emissions of different systems and environmental impacts of different systems.

Life cycle assessment (LCA) of three alternative rice farming systems was performed by (Blengini and Busto, 2009) in order to determine the magnitude and the concentrated point of the impact of one kilogram of delivered rice. Life cycle impact assessment of the study focused on the indicators of "gross energy requirement, net renewable energy requirement, global warning potential, ozone depletion potential, acidification potential, eutrophication potential, photochemical ozone creation potential, total water use and the direct water use". They concluded that I kilogram of exported white milled rice consume 17.8 MJ of primary energy, produce 2.9 kg of CO_2, and use about 4.9 m^3 of total water consumption.

Meisterling et al. (2009) studied the differences in the greenhouse gases emission from organic and conventional wheat production with specific emphasis on the transportation of the inputs and the output. Similarly Fukushima and Chen (2009) discussed the greenhouse gas emission from the cultivation of sugarcane cultivation in Taiwan and they concluded that the highest source is the denitrification in the ecological system during the cultivation of sugarcane which accounts about 50.5 percent.

2.7.3 LCA existing research on water use in crop production

In order to estimate the environmental impact of the water used in irrigation systems, (Milà i Canals et al., 2009) suggested that the evaporative and non-evaporative use of blue and green water should be distinguished and quantified along with the land use change as it effect the availability of fresh water. They also pointed out that different environmental system analysis tools like life cycle analysis (LCA) and virtual water (VW) calculation can measure the amount of water use in the production systems of any product. Both of these tools have lack of proper assessment of relative scarcity and opportunity cost of water at the point of production of a product. The sources of water to the production system should be distinguished and the way or the condition to which water leaves the product system should also be documented.

Pfister et al. (2009) suggested that in the life cycle analysis of cotton production, the consumptive and non-consumptive use of water, the source of water and the geographical location of the water should be addressed separately. While considering the water as an input in the irrigation system, the main areas of protection are the human health, ecosystem quality and water as natural resource should be considered as discussed by (Milà i Canals et al., 2009) in the life cycle analysis of a crop production system. Milà i Canals et al. (2009) concluded that the green water is essential for the calculation of VW in order to calculate the total water use but green water is not included in life cycle impact assessment (LCIA). The impact of green water is not considered in the LCA of the irrigation system even it is available to the plants. They only considered the direct use of blue water in order to consider its impact on human health, ecosystem quality and the freshwater depletion (FD). The cotton crop production enhances the freshwater resource depletion and degradation in different ways and thus ultimately affects the ecosystem quality and human health.

The low intensity crop production is environmentally favorable, could be followed by low productivity of the crop and thus leads to the shifting of the pollution to the other regions. Based on the mentioned assumption the optimal combination of variety of fertilization and land utilization and other energy inputs is necessary (Charles at el., 2006).

2.8 Efficiency analysis in agriculture using Data Envelopment Analysis

Data Envelopment Analysis (DEA) has been used in agricultural case studies only recently with pioneering works by De Koeijer et al. (2002) and Reig-Martínez and Picazo-Tadeo (2004). Cropping systems are typical DMUs because they mobilize a set of production factors (e.g., land, labor, agro-chemicals, mechanisation, and water) and result in a set of outputs (e.g., yield, environmental impacts, income).

Wossink and Denaux. (2006) compared the environmental and cost efficiency of pesticide use in transgenic and conventional cotton production in North Carolina, USA by mean of DEA. They considered the environmental impact as input not as undesirable output. The model they used was similar to the model of technical efficiency, the only difference was instead of using the amount of observed input, and the expected corresponding environmental impact of each input category was used. With the help of DEA methodology they developed an environmental efficiency index taking into account all different pesticides categories.

Nassiri and Singh. (2009) studied the energy use efficiency for paddy crop production using data envelopment analysis (DEA) technique. They used the output oriented DEA model and compared the technical efficiency of different sources of energy use in marginal, small, semi medium, medium and large farmer. They also performed zone wise comparison of the technical efficiency of human, animal, fossil fuel, electricity, machinery and chemical fertilizers and pesticides.

2.9 Environmental impacts and techno economic performances: Eco-efficiency analysis

Different studies have been conducted to make a link between environmental impacts and the economic performance of production systems through eco-efficiency analysis. In order to assess the eco-efficiency one should know the amount of the certain input being used to produce a certain amount of output. In term of the physical units it is considered as the technical performance of any system. However after translating the inputs and output into monetary terms the economic performance can be assessed. Lauwers, (2009) justified eco-efficiency analysis using material balance principle introduced by Coelli et al., (2007). Bassset-Mens et al., (2009) analyzed eco-efficiency of milk production in New Zealand using potential environmental impact indicators calculated through LCA methodological approach. But they performed eco-efficiency based individual environmental indicators without using any method to aggregate the eco-efficiency into a single value. Picazo- Tadeo et al. (2010) and Gómes et al. (2012) analyzed eco-efficiency of farming systems using ad-hoc environmental indicators through DEA approach.

Vázquez-Rowe et al. (2010) introduced a five step methodology to combine Life Cycle Assessment (LCA) with Data Envelopment Analysis (DEA) in order include eco efficiency verification with assessment of environmental performance. They recommended the five steps methodology of LCA+DEA in order to avoid the averaged inventories. The averaged inventories some time cause the problem of large standard deviation (Lozano et al., 2009). The LCA+DEA method adds the economic dimension together with the environmental performance that can help to quantify the operational inefficiencies which leads to better environmental performance. The five steps proposed by Vázquez-Rowe et al. (2010) are given as follows. Avadi and Vázquez-Rowe, (2014) analyzed eco-efficiency of Peruvian fishery by using five steps method developed by Vázquez-Rowe et al. (2010).

Chapter 3

Methodology

This chapter describes the methodological details that were applied to investigate the techno economic and environmental performances and efficiencies of selected cotton cropping systems in Punjab, Pakistan. The beginning of this chapter deals with the selection of the study area followed by the data collection methods. In the subsequent sections analytical details are elaborated.

3.1 Methodological framework

To accomplish the objectives of the study the methodological framework is based on the combination of several tools and approaches. It starts with the selection of the study area and cotton cropping systems. The data collection methods, data analysis and the definition of results discussions have been performed based on six building blocks of the methodological framework.

Primary data collected through field survey was used to develop techno-economic indicators and assess the performances of these systems. These indicators have been developed based on physical and monetary values of different inputs per unit area of cotton cropping systems. These indicators are further used to analyze technical and cost efficiencies of different systems, and their efficiencies have been compared.

To assess the environmental performances, ad-hoc environmental indicators have been developed with the help of the input and output data of the farms. These indicators are used to assess the environmental efficiencies of cotton cropping systems. Beside these ad-hoc environmental indicators, LCA-based environmental impacts of these systems have also been measured. Environmental impacts indicators have been calculated based on per unit area of crop grown as well as per unit output produce. These indicators have been used to analyze the eco-efficiency of different systems. All these tasks of assessing techno-economic and environmental performances of cotton cropping systems are explained in the following sections.

Figure 3.1 shows the following six building blocks that form the overall methodological framework.

1. Site selection and sampling
2. Data collection
3. Performances analysis (LCA-based, with ad-hoc indicators, and techno economic analysis
4. Efficiency analysis with DEA
5. Analysis of factors affecting efficiencies and
6. Final discussion and synthesis

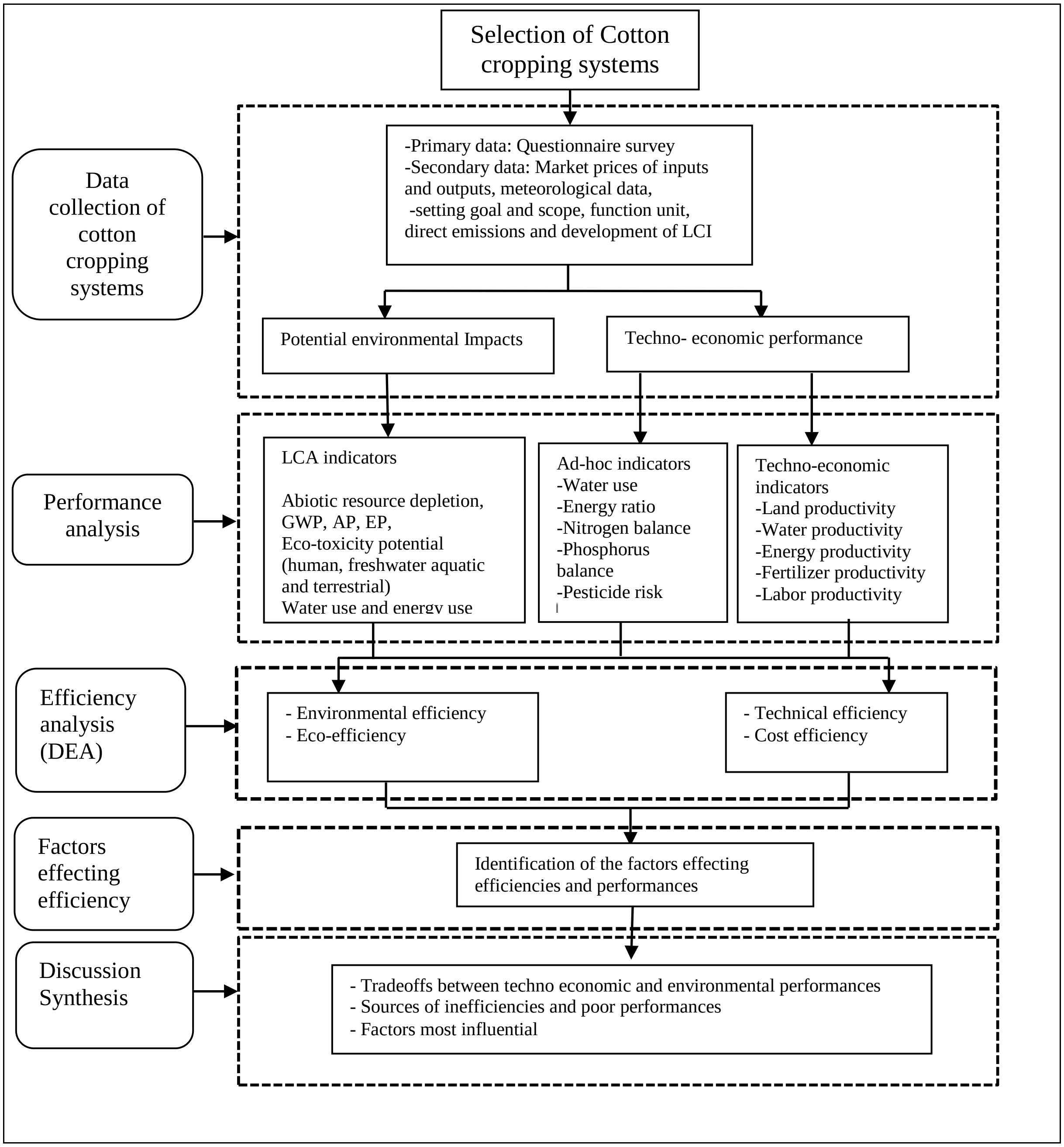


Figure 3.1 Methodological framework of the research

3.2 Description of the study area

The study has been conducted in Punjab province of Pakistan and this province contributes 80% to the country's total cotton production. Cotton is mainly grown in the southern part of the province, which is most suitable for cotton cultivation (Ali and Abdulai, 2010). There were three main reasons to select the Punjab province of Pakistan for this study. First, it has strong cotton based cropping systems and is considered the core cotton growing area, second the existence of a mix of intensified and less intensified cropping system and third diversified forms of cotton cropping system exist in this area.

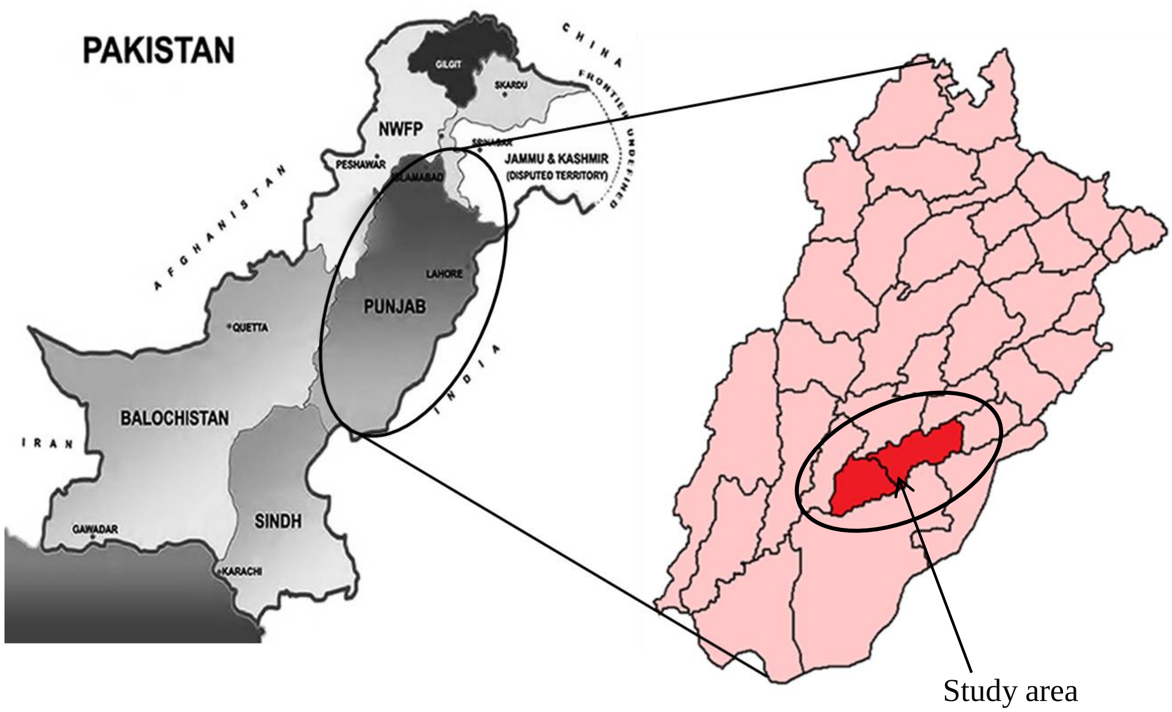


Figure 3.2 Location of the study area in Pakistan

3.3 Data requirement and data sources

A variety of data is required in order to assess the techno economic and environmental impacts of cotton cropping systems. The systems under study are divided into on-farm and off-farm sub systems in order to classify the source of data and the data requirements according to the activities performed and the resources used at different stages of cotton crop production. Detailed data of different inputs (land, irrigation water, energy, machinery, labor, fertilizers, pesticides etc.) were collected through farmer's interview and direct observation. The cost of different inputs used in cotton cultivation as well as the price of the seed cotton (un-ginned picked cotton) at farm gate was required. Primary data was collected from farmers through questionnaire survey and secondary data from Economics and Marketing Department of Pakistan.

Table 3.1 Primary data collection

Category	Data Collected	Source
Farm operations		
Tillage operations	Machinery used (type, time used and fuel consumption)	Field survey
Seeding	Seed rate	
Fertilization	Fertilizers applied (type and timing of fertilizers applied)	
Weeding	Mechanical and manual weeding	
Pesticides (Insecticides and herbicides) applications	Doses of agro-chemicals Active ingredients/ composition of agro-chemicals	
Human labor	Labor mobilized	
Water use	Irrigation water	
Variables costs	Unit costs of variable inputs	
Picking	Yield (seed cotton, sticks) and price of seed cotton	
Farm and farmer's Characteristics	Plot size + farm size Sowing methods, Land tenure system (tenant operator versus owner operator) Education level of decision makers, head Age of decision maker, head	Field survey

Table 3.2 Secondary data collection

Category	Data required	Data source
Meteorological data	Temperature (mean, maximum and minimum monthly temperature) Rainfall (mean monthly rainfall) Relative humidity in percentage Sunshine duration (monthly means of sunshine hours) Wind speed	Meteorological Department
Economics	Market prices of inputs and outputs Crop calendar	Marketing and Economics Department

3.4 Sampling and data collection strategy

Cotton crop is commonly rotated with wheat crop in Punjab. Sowing of cotton may occur during the period of late April until mid of June but mostly sowing is performed during May as shown in figure 3.3. There are two different methods of cotton cultivation: 1) cotton is grown on flat seed bed and is irrigated through flood irrigation or 2) cotton is sown on raised bed and is irrigated through furrows. It is claimed that less water is required in raised bed sowing compared to flat seed bed sowing. Energy requirements are also different between these sowing methods.

Data regarding mechanization, energy and water consumption, fertilizers, pesticides and other agrochemicals application, and crop management practices were collected from the selected farms. The timings, frequency and the amount of different inputs and information related to cost of inputs, yield and the price of output were also collected from field survey.

The sampling strategy consisted in trying to cover the diversity of situations at the farm level, including different levels of mechanization and intensification and also different sowing methods. The underlying hypothesis is that those different systems generate wide ranging impacts. Addressing farm level diversity is deemed to help better analyze the sources of such impacts. The level of intensification and mechanization depends upon the size of land holding and the financial status of the farmers.

Field data was collected through a structured questionnaire shown in Appendix C. A semi structured questionnaire was first tested in the field and then used to interview individual farmers. The questionnaire was structured mainly to record the consumption of all production factors (inputs per ha) used during the cropping season of 2010-2011, including labor, seed, machinery, fuel consumption, fertilizers and pesticides. Also, yields of seed cotton (i.e., un-ginned picked cotton) were recorded. Initially field level data of 200 farms was recorded. Some questionnaires were ultimately discarded because of missing data and 169 cropping systems (as DMUs) remained and were mobilized for analyzes. Different farm categories were selected randomly, including small (less than 5 hectares), medium (5 to 20 hectares) and large (greater than 20 hectares) farms. Such classification refers to the land holding classification of State Bank of Pakistan. Lodhran and Vehari districts of southern part of Punjab province were selected because both these districts belong to the core cropping zone of the province.

		Cropping calendar											
No	Activities	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Ploughing												
	Pre-sowing Irrigation[1]												
	Seedbed preparation												
	Weedicide application[2]												
	Sowing												
	Fertilization (DAP)[3]												
	Fertilization (Urea)[4]												
	Irrigation[5]												
	Hoeing/ mechanical weeding												
	Pesticide application[6]												
	Picking[7]												

Figure 3.3. Cropping calender

1. In flat seed bed sowing method the field is irrigated before sowing.

2. Herbicides are applied in field just before sowing.

3. Mostly Diammonium Phosphate (DAP) is applied at the time of sowing or at the 2nd irrigation after sowing.

4. Urea is applied alternatively during irrigation.

5. The first irrigation is applied after 4 days in case of raised bed sowing; however in case of flatbed sowing method the first irrigation water is applied after 35-40 days. Later on the water is applied after 8th or 10th day's interval.

6. Pesticides are applied both manually and mechanically

7. Picking starts from September and ends in first half of November

3.5 Assessing water use

The cotton crop water requirements are partially fulfilled by the gravitational flow of surface water through canal systems diverted from Indus River or from its tributaries and partially fulfilled by groundwater pumping. As it is impossible to collect irrigation water consumption data directly from farmers, because they are not aware of the actual volume of water being used in their farms and there are no measuring device. Therefore, water use has been estimated modeling the crop water requirements. To quantify the water use of cotton crop during crop growth period, methods of irrigation water application are very important. The sources of irrigation water are blue water i.e. surface and groundwater and green water that is the effective natural rainfall and soil water stocks.

Climatic data was required in order to assess crop water requirement and was collected from Meteorological Department. Green water or effective rainfall is the volume of rain water infiltrated in soil and is taken up by the plant from the soil. Total volume of green water has been calculated by mean monthly rainfall data during entire crop growth period. USDA soil conservation service method has been used to assess the effective rainfall.

The irrigation water or blue water is the amount of water artificially supplied to cotton crop in addition to effective rainfall. The blue water use has been calculated through crop evapotranspiration from sowing until harvest. Cotton crop evapotranspiration (ET) has been calculated through CROPWAT (FAO, 1992). Average monthly meteorological data has been taken from Meteorological Department of Pakistan. Potential evapotranspiration or reference evapotranspiration (ET_0) has been estimated through Penman-Monteith method and the equation is given as below.

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{900}{T+273} u_2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.034u_2\right)} \qquad \textit{(Equation 3.1)}$$

Where ET_0	is reference crop evapotranspiration	[mm/day]
R_n	is net radiation at the crop surface	[MJ m-2 day-1]
G	is soil heat flux density	[MJ m-2 day-1]
T	is mean daily air temperature	[°C]
u_2	is wind speed at 2-m height	[m/s]
e_s	is saturation vapor pressure	[kPa]
e_a	is actual vapor pressure	[kPa]
Δ	is slope vapor pressure curve	[kPa/°C]
γ	is psychometric constant	[kPa/°C]

Actual evapotranspiration (ETa) can be calculated through the ET_0 and Kc which has been calculated through the Meteorological Data as follows:

$Et_a = ET_0 \times K_c$

Where “Kc” is crop coefficient and it reflects the physiological stage of the crop, which influences its water requirement.

3.6 Assessing energy use

Different inputs are used in cotton crop production processes and each of these different physical inputs has its unique energy coefficients and their corresponding values are given in table 3.3. The amount of energy used in field operation depends on different physical factors as well as farmers’ decisions. Energy use is a function physical factors such as soil characteristics, weather, irrigation water availability, insect pest invasion and farming practices.

Table 3.3 Energy coefficient of various farm inputs

Classification	Energy equivalent	units	Source
A. Direct energy inputs			
Human labor	1.96	MJ/man-h	Singh et al. (2002)
Diesel fuel	56.41	MJ/L	Mandal et al (2002, Yilmaz et al (2005), Hatirli et al (2006) and Singh et al (2002)
Electricity	42.95	MJ	Nassiri et al (2009)
B. Indirect energy inputs			
Nitrogen (N)	60.60	MJ/kg	Singh and Mittal (1992)
Phosphorus(P_2O_5)	11.10	MJ/kg	Singh and Mittal (1992)
Potassium (K_2O)	6.7	MJ/kg	Singh and Mittal (1992)
Insecticides	184.63	MJ/kg	Pimentel (1980)
Herbicides	254.45	MJ/kg	Pimentel (1980)
Fungicides	97.0	MJ/kg	Pimentel (1980)
Sulphuric acid	3 MJ/kg	MJ/kg	Armaroli & Balzani (2011)
Cotton seed	11.8	MJ/kg	Dagistan et al (2009) and Ozkan et al (2004)
Cotton stalk	17.88	MJ/kg	Kumar and Kandpal (2007)

The energy of machinery was calculated by equation 3.1 (Ozkan et al., 2004; Mikkola & Ahokas, 2010; Ozkan et al., 2004; Canakci, 2010 and Mohammadi & Omid, 2010).

ME = E (G/T) *(Equation 3.2*

Where ME is the mechanical energy (MJ/h) that is E = 62.7 MJ/kg production of machine, G is the weight of Machine (kg) and T is the economic life (years) of machine.

Total chemical energy of fertilizers has been calculated on the basis of the respective percentages of the Nitrogen (N), Phosphorus (P_2O_5) and Potassium K_2O present in individual fertilizer. Sulphuric acid is used for delinting of the seed before sowing contain 3 MJ/kg of energy (Armaroli, & Balzani, 2011).

The main output of the cotton crop is the seed cotton (unginned picked cotton). The cotton stalk is a byproduct of the cotton crop that is generally used as fuel wood. The energy coefficient of the seed cotton is taken as 11.8 MJ/kg reported by Dagistan et al. (2009) and energy coefficient of cotton stalk is taken as 17.88 MJ/kg proposed by Kumar and Kandpal

(2007). All these energy inputs and energy outputs have been computed in order to compute energy ratio as an ad-hoc indicator.

3.7 Development of ad-hoc technical and environmental indicators

With the help of the data gathered though methods discussed in the previous section, indicators for environmental impact and efficiency have been developed following the methodology developed by Picazo-Tadeo et al. (2011), Picazo-Tadeo et al. (2012) and Gómez-Limón et al. (2012). It was decided to use farm level indicators of environmental impacts in order to simplify environmental impact assessment and comparing with the more demanding LCA approach. Efficiency analysis was first upon such indicators. Net income per hectare was used as an output instead of the physical product (seed cotton) or total revenue, which includes production costs. To calculate the technical efficiency, the physical quantities of water (volume), seed (mass), labor (time), fossil fuel (volume), nitrogen, phosphorus and pesticides (mass) have been used. To calculate the cost efficiency, the prices of the above-mentioned inputs except water have been used. Table 3.2 recaps the different variables that were used, their units, and methodologies or sources used for the calculations.

Table 3.4 Cotton cropping inputs, units, and methods or sources used for the calculations

Input	Units	Method or source for calculation
Water	cubic metre (m^3)	CropWat (FAO)
Seed	kilogram (kg)	Primary data (field survey)
Labor	man-hours	“
Fossil fuel	Liter	Primary data and conversion standards
Nitrogen	kilogram (kg)	Primary data (field survey)
Phosphorus	kilogram (kg)	“
Pesticides	gram (g) of active ingredients	“

In order to assess the synoptic environmental efficiency some ad-hoc variables have been developed. All but one of the variables were adopted from Picazo-Tadeo et al. (2011), Picazo-Tadeo et al. (2012) and Gómez-Limón et al. (2012). One additional variable, water use, was selected because water use is a very important environmental indicator due to water scarcity in arid Pakistan. The following ad-hoc variables were used to assess the environmental efficiency of each cropping system as suggested by Picazo-Tadeo et al. (2011), Picazo-Tadeo et al. (2012) and Gómez-Limón et al. (2012).

a. Water use

This indicator is the amount of water in cubic metre (m^3) used per hectare by each cropping system throughout the cropping season. Because there is no measuring device for individual farm water consumption in Punjab, the cotton crop irrigation water requirement (IWR) was used as a proxy for actual water use. The IWR was calculated using CropWat software (FAO, 1992), assuming field application efficiency Ea of 75%, canal conveyance efficiency Eb of 75%, and a water-course conveyance efficiency of 70%, in accordance with Hussain *et al*. (2011).

b. Energy ratio

The energy ratio (ER) is the ratio of energy input to output (Equation 3.3). The energy input is the amount of energy used per hectare, mostly in the form of fossil-fuel consumption by machinery and agrochemicals used, including the energy equivalent content (the indirect energy use or embodied energy use); the energy output is the amount of energy equivalent for cotton seed and cotton stalk. The energy input and output were calculated in mega joules (MJ/ha) (Pimentel, 1980). The higher the energy ratio, the lower the energy efficiency of a given cropping system.

$$Energy\ ratio = \frac{Energy\ input\ (MJ/ha)}{Energy\ output\ (MJ/ha)} \qquad (Equation\ 3.3)$$

c. Nitrogen balance

The nitrogen balance was calculated based on the difference between the total amount of nitrogen applied per hectare (as fertilisers) and the total nitrogen exported by seed cotton at the time of harvest (see Equation 3.4). Both nitrogen input and output were calculated in kilograms per hectare (N kg/ha). The nitrogen balance provides a metric that quantifies the amount of nitrogen released into the environment. The higher the nitrogen balance, the higher the potential environmental impact due to nitrogen for a given cropping system.

$$Nitrogen\ Balance\ = Nitrogen_{input} - Nitrogen_{Output} \qquad (\ Equation\ 3.4)$$

d. Phosphorus balance

A similar approach was applied to measure the phosphorus balance for each cropping system (see Equation 3.5). The phosphorus balance is expressed in kilograms per hectare (P_2O_5 kg/ha). This indicator helps to quantify the contribution of cotton farming to eutrophication by phosphorus pollution. The higher the phosphorus balance, the higher the potential environmental impact.

$$Phosphorus\ Balance\ = Phosphorus_{input} - Phosphorus_{output} \qquad (\ Equation\ 3.5)$$

e. Pesticide risk

The data for the pesticides used by each farmer is available, but quantifying the environmental impacts of the chemical used per hectare is difficult due to its characteristic non-point source. Therefore, a pesticide risk indicator that determines the overall toxicity of the pesticides released into the environment was used to measure the potential environmental risk of each category of pesticide [i.e., the insecticides, herbicides and fungicides used on each farm (as done by Picazo-Tadeo et al., 2011, Picazo-Tadeo et al., 2012, and Gómez-Limón et al., 2012)].

$$Pesticide\ Risk = \sum_{m=1}^{M} 1000\, \frac{Amount\ of\ pesticide\ active\ ingredients_m^k\ (g/ha)}{Lethal\ dose\ 50m\ (g\ /kg\ rat)} \qquad (Equation\ 3.6)$$

The pesticide risk was calculated by dividing the quantity of active ingredients in the pesticide ‘m’ (g/ha) applied to the cotton crop in farm ‘k’ and the so-called “lethal dose 50”, which is the amount of pesticide product ‘m’ sufficient to kill 50% of a rat population in milligrams of pesticide product per kilogram of rat body mass (see Equation 3.6). If the value of this indicator increases, the environmental impact of that farm also increases, which indicates that more toxic pesticide products were used on that farm.

3.8 Development of environmental impact indicators with LCA

Eco-efficiency analyzes have been performed based on the impacts computed through Life Cycle Assessment (LCA) approach. Eco-efficiency is the ratio of economic value and the corresponding environmental impact of a product. The added economic value has been calculated based on cost of inputs used in cotton production and revenue generated from the physical output.

LCA methodological approach has been used to assess the potential environmental impacts of different cotton cropping systems. The International Organization for Standardization (ISO 14040, 2006) set up the four stages of life cycle assessment framework as presented below.

3.8.1 Goal and scope, system boundary and specification of the analysis

The main aim of this study is to assess existing cotton cropping systems in Pakistan with regards to assess their potential environmental impacts. To this end cotton farming systems with different intensification and mechanization levels were selected. Techno economic and environmental performances have been analyzed on per hectare basis. Further environmental impact indicators have been mobilized in eco-efficiency analysis.

The goal of this study was set to assess and analyze the resources use, energy consumption (renewable and non-renewable energy) in the field operations and water consumption during growth period of cotton crop. The production, transportation and handling of the main inputs are also considered as a part of the system. The emissions of these inputs are also part of the system. Field data have been collected to assess technical as well as economic performances of the systems. The relationship among these performances have been analyzed and finally best compromise practices to optimize the system (maximizing the economic return at farm level from production and minimizing the environmental impacts) has also been identified. The functional unit of 1000 kilogram of seed cotton (un-ginned picked cotton) was selected to assess the environmental impacts per mass of seed cotton produced. In order to compare the yield effect on per area unit among different cropping systems, per hectare environmental impacts have also been analyzed.

Cradle to farm gate approach has been adopted for this study. The system boundary of the present study includes the production and transportation of different inputs and activities that are performed at farm level. The use of blue water (surface water or groundwater) was analyzed together with green water in order to assess the actual irrigation water requirement of cotton crop with the help of the data collected from the field and from secondary sources. All variable inputs such as fuel consumption during different management and cultural practices, electricity consumption for water pumping, pesticide and fertilizer uses been considered.

Raw product transport and further processing beyond the farm level were not considered in this study. The farm house, farm roads and the drainage network were not considered as the part of the system since they have other functions. Cotton is mainly grown for fiber production but fiber is not the only output of cotton crop. Cotton seed and cotton stalk are by-products of cotton crop. Economic allocations criteria by giving economic value to each product based on the market prices have been adopted to compute logical share of environmental impact of seed and lint. Cotton stalk was not given any share of environmental impact as it does not have any market price.

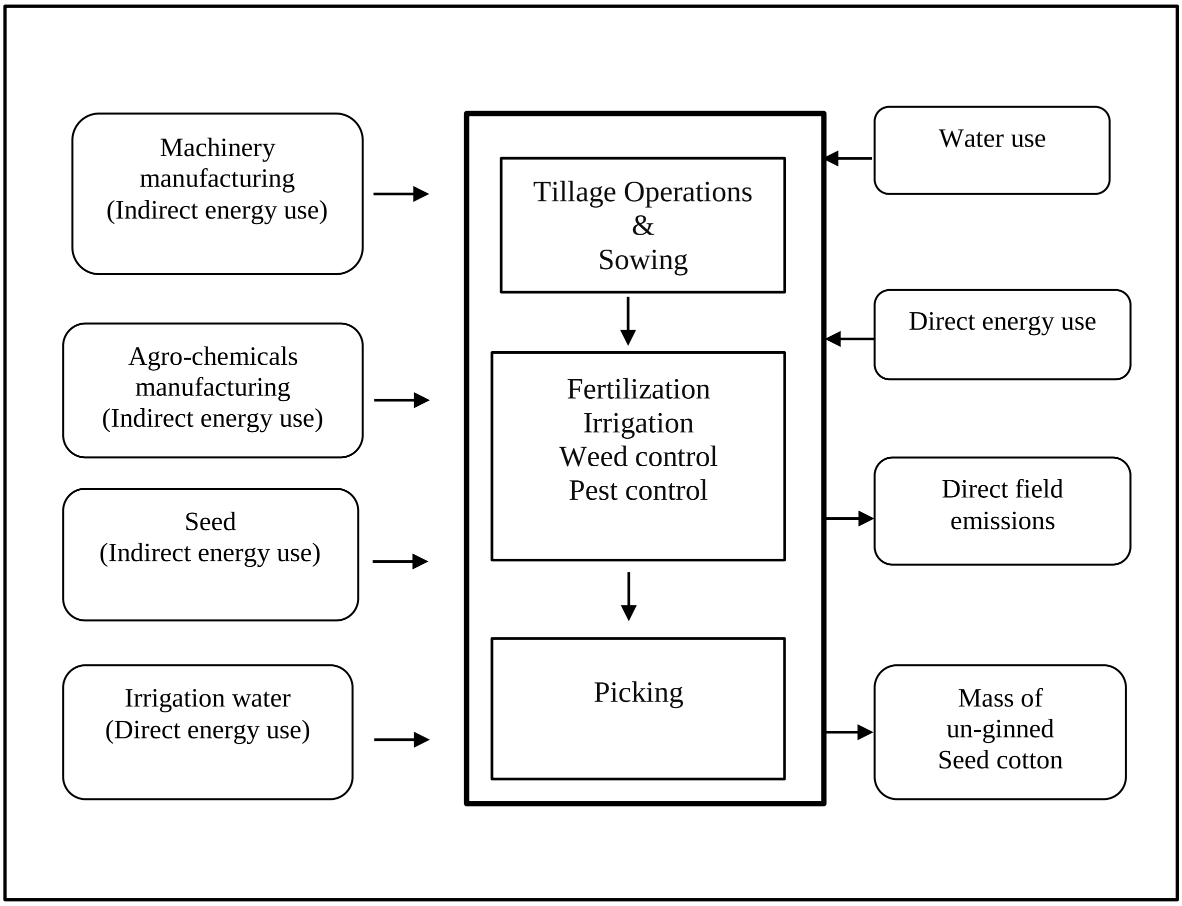


Figure 3.4 System boundaries of cotton production systems from cradle to farm gate

3.8.2 Life cycle inventory

Different activities are performed and different inputs are required at field level as well as at the production, processing and transportation of the inputs used in the production of cotton. The life cycle inventory is based on the diversified farm of cropping system depending upon the level of intensification of the farm.

The data for the quantity and frequency of different operations and inputs have been computed through field survey data as shown in table 3.4. Direct field emissions from crop production practices have been modeled and discussed in detail in chapter 6. The resource depletion is another issue linked with these operations i.e. water and non-renewable energy resources depletion.

Table 3.5 Cotton cropping inputs, units, and methods or sources of data.

Input	Units	Method or source for calculation
Tillage operations	hour/ha	Primary data (field survey)
Rotary tillage	hour/ha	“
Field leveling	hour/ha	“
Sowing	hour/ha	“
Weeding	hour/ha	“
Electricity consumption	KWh/ha	“
Nitrogen fertilizers	kilogram (kg)/ha	“
Phosphorous fertilizers	kilogram (kg)/ha	“
Potassium fertilizers	kilogram (kg)/ha	“
Zinc sulphate	kilogram (kg)/ha	“
Pesticides unspecified	gram (g) of active ingredients /ha	Primary data and conversion standards
Organophosphates	gram (g) of active ingredients /ha	“
Parathyroid	gram (g) of active ingredients /ha	“
Phenoxy compound	gram (g) of active ingredients /ha	“
Herbicides	gram (g) of active ingredients /ha	“

3.8.3 Impact Assessment through mid-point impact indicators

Life Cycle Impact Assessment (LCIA) stage translates the information collected during LCI phase into impact indicators. In Life Cycle Inventory (LCI) of all the material inputs has been computed with the help of primary data collected through field survey and the field emission to water, air and soil was modeled as discussed in chapter 6. SimaPro 7.2.3 software application and Ecoinvent database has been used to implement Life Cycle Impact Assessment (LCIA) using CML 2001 method in order to compute the following environmental indicators: Abiotic depletion potential (ADP), Global warming potential (GWP), Acidification potential (AP), Eutrophication potential (EP), Human toxicity potential (HTP), Fresh water aquatic ecotoxicity potential (FETP), Terrestrial ecotoxicity potential (TETP), Water use (WU) and energy use (EU). All these environmental impacts indicators are popular in LCA studies because these indicators address global level impacts and local level impact. Table 3.5 shows the LCIA characterization indicators of cotton farming in Punjab, Pakistan.

Table 3.6 Selected impact categories in LCIA of cotton

Environmental impact categories	Units
Abiotic depletion potential (ADP)	Kg Sb eq
Global warming potential (GWP)	kg CO_2 eq
Acidification potential (AP)	SO_2 eq
Eutrophication potential (EP)	PO_4^{3-} eq
Human toxicity potential (HTP)	1,4-DB eq
Fresh water aquatic ecotoxicity potential (FETP)	1,4-DB eq
Terrestrial ecotoxicity potential (TETP)	1,4-DB eq
Ozone layer depletion (ODP)	kg CFC-11 eq
Photochemical oxidation potential (PO)	kg C2H4 eq
Energy Use (EU)	MJ
Water use (WU)	m^3

3.8.4 Interpretation of the results

In the fourth stage of Life Cycle Assessment the result of LCIA has been interpreted in order to find out different hotspots of the environmental impacts of cotton cropping systems through analyzing the environmental impacts of cotton production sub-systems.

To take the effect of different levels of input on undesirable output (pollutant emissions to the surrounding environment) or on the economic desirable output (cotton yield), variability exists and to quantify it careful considerations are required. Data variations experienced from farm to farm and these variations cause different level of environmental impacts.

3.9 Approaching efficiency with DEA

Efficiency has emerged as a practical concept to approach and measure the sustainability of industrial (Callens and Tyteca 1999) and agricultural (De Koeijer et al. 2002) production systems, because efficiency analyzes may combine environmental and economic components and provide quantitative metrics.

Data envelopment analysis (DEA) in a non-parametric approach initially developed by Charnes et al. (1978) to calculate the relative efficiency of a set of production and/or management units (hereafter called decision-making units or DMUs). The overall idea is to comparatively measure how these units generate outputs while mobilizing inputs. Because the inputs and outputs were originally technical in nature, the early authors referred to this concept as technical efficiency.

The basic idea of calculating the relative efficiency of a set of DMUs is to construct a piecewise frontier; all of the efficient DMUs lie on the frontier, and the DMUs below the frontier are considered to be inefficient. DMUs efficiency score range between 1 (full efficiency) and 0 (full inefficiency).

The production frontier symbolises the minimum input requirement to produce a certain amount of output. A cost frontier describes the minimum cost incurred to produce a certain amount of output (Nguyen et al. 2012), and the environmental efficiency represents the minimum production environmental impacts or undesirable outputs without compromising the given level of desirable output.

Cropping systems are typical DMUs because they mobilize a set of production factors (e.g., land, labor, agro-chemicals, mechanisation, and water) and result in a set of outputs (e.g., yield, environmental impacts, income). DEA has been used in agricultural case studies only recently with pioneering works by De Koeijer et al. (2002) and Reig-Martínez and Picazo-Tadeo (2004).

There are three approaches to efficiency with DEA. The first aims at seeking a reduction of the amount of input for producing a constant output (input-oriented DEA); the second aims at seeking an increase of the output while maintaining the level of input (output-oriented DEA); the third is a mixed approach of reducing input while increasing output. Regarding agricultural production, farmers only control the amount of inputs they use; therefore, the input-oriented efficiency model was selected for technical and cost efficiency analysis.

All DEA based efficiency analyzes in this study have been performed with MaxDEA Pro a Data Envelopment Analysis software developed by Gang and Zhenhua (2013).

3.9.1 Input-oriented technical efficiency

Input-oriented technical efficiency was developed by Charnes et al. (1978) and is called the CCR model, after the initials of the authors. In CCR model a farm or a DMUj produces a vector of y desirable outputs denoted by y = (1,2,…,S) $\in \boldsymbol{R}_{+}^{S}$ by using vector of input x = (1,2, …, M), $\in \boldsymbol{R}_{+}^{M}$. As proposed by Cooper et al. (2007), the technical efficiency was calculated by using the following DEA model:

$Minimize\ \theta$

Subject to

$$\theta x_j - X\lambda \geq 0 \qquad (Equation\ 3.7)$$

$$Y\lambda \geq y_j$$

$$\lambda \geq 0$$

where $'\theta'$ is a scalar and its value is the technical efficiency value of the 'j^{th}' farm and 'λ' is the intensity vector of the weights of efficient DMUs, which helps to project inefficient DMUs to an efficient frontier. The data for all n farms or DMUs in the sample is represented by m × n input matrix X and s × n output matrix Y where 'x_j' represents the input vector of the j^{th} farm and 'y_j' represents the desirable output vector of j^{th} farm.

When all the three usual assumptions (convexity, scalability and free disposability) of DEA are met, the production possibility set refers to a constant return to scale (CRS) and if the third assumption of scalability is not met then the production possibility set refers to variable return to scale (VRS). The equation 2 above assumes constant return to scale because all three mentioned assumptions are met. However farming is considered a typical variable return to scale activity because of the potential economies of scale. Adding an additional constraint of $\sum \lambda_j = 1$ in equation 2 leads to a variable return to scale frontier and is called pure technical efficiency (also called BCC model after the initials of the authors) developed by Banker et al. (1984), which can separate technical and scale efficiencies.

A variable return to scale model does not indicate whether an inefficient DMU is operating in the region of increasing or decreasing return to scale. This problem can be solved by applying an additional model called non-increasing return to scale (NIRS), which is modelled by adding a constraint $\sum \lambda \leq 1$ in equation 1 (Cooper et al. 2007). Comparing the TE_{CRS} and TE_{NIRS} helps to determine whether the production is characterized by decreasing or increasing return to scale. If $TE_{CRS} < 1$ and $TE_{CRS} = TE_{NIRS,}$ inefficiency is resulting from increasing return to scale i.e the farmer is producing at an inefficiently small output level. If $TE_{CRS} < 1$ and $TE_{NIRS} > TE_{CRS}$ inefficiency is caused by operating inefficiently large output level (Wossink and Denaux 2006).

3.9.2 Cost Efficiency

Cost efficiency can be calculated through a cost-minimising model, in which the cost of each input per hectare (ha) is used instead of using physical units for those inputs. The cost-minimising approach leads to the cost efficiency of cotton cropping systems with the help of strictly positive vector of input price w = $(w_1, w_2, \ldots, w_M) \in R_+^M$. In the cost minimization model the m × n input matrix ‘x’ is transformed into ‘$w^/x$’ where ‘$w^/$’ is the transpose of input price vector. The cost efficient frontier provides the minimum expenditure required to produce given output.

The cost efficiency (CE) can be used to derive the cost allocative efficiency (CAE) with technical efficiency (TE). This derivation can help to reveal sources of improvement, which are a proportional decrease in the input vectors and a cheaper input mix. Cost allocative efficiency (CAE) is the ratio of cost efficiency (CE) to technical efficiency (TE).

$$CAE = \frac{CE}{TE} \qquad (Equation\ 3.8)$$

The decomposition of the cost efficiency into technical efficiency and allocative efficiency indicates the sources of inefficiencies. TE refers to the proportional decrease of the input vectors however CAE relates to the least cost combination of inputs.

Figure. 3.4 below is a simple illustration of the relationship between two inputs (x1 and x2) and one output y. The ‘cc’ line indicates iso-cost line and ‘ss’ indicates the isoquant curve. As explained by Coelli et al. (1998), if a production process generates a quantity of output by using the inputs ‘x1’ and ‘x2’ represented by point ‘p’, then technical inefficiency of that firm under constant return to scale assumption is the distance ‘qp’, which means that both the inputs can be reduced proportionally without reducing the amount of output. In percentage term the technical inefficiency of a production process is the ratio of ‘qp/op’ and hence technical efficiency can be calculated by subtracting the amount of computed inefficiency from 1, which is equal to the amount of ‘oq/op’.

The cost efficiency can be computed with the help of iso-cost line and cost efficiency is the ratio of or/op where ‘rp’ is the distance that represents the amount of proportional cost reduction. Allocative efficiency can be computed by the ratio of cost and technical efficiency, which is defined as ‘or/oq’. Under the assumption of variable return to scale or non-increasing return to scale the efficiency can be explained in similar way.

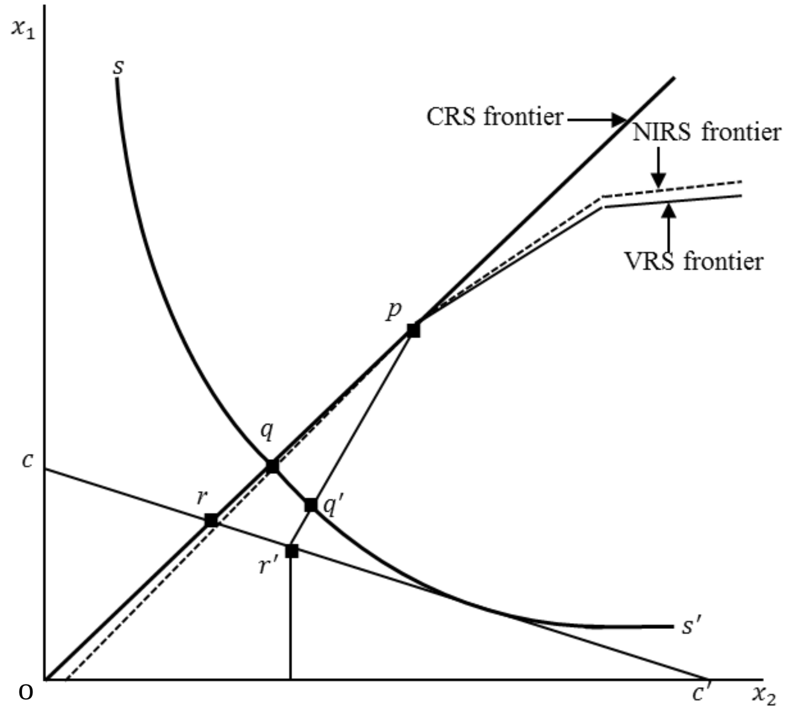


Figure 3.5 Input oriented efficiency frontiers and representation of overall, technical and allocative efficiencies

3.9.3 Environmental efficiency

The model supposes that a farm or a DMU uses a vector of inputs x = (1,2, …, M), ∈ $\boldsymbol{R}_+^M$ in the production process and produce desirable output y = (1,2, …, S), ∈ $\boldsymbol{R}_+^S$ and undesirable outputs or environmental impacts b = (1,2, …, P), ∈ $\boldsymbol{R}_+^P$ then the production technology is given by:

T = [(*x, y, b*): *x* produce (*y, b*)]. *(Equation 3.9)*

In order to reasonably model the environmental efficiency of the DMU, one produce a certain amount of desirable output by using as minimum amount of inputs as possible and thus to produce as minimum amount of environmental impacts as possible. The reference technology can provide all feasible relationships between multiple inputs and multiple outputs and it can be modelled either by means of output set or input set (Picazo-Tadeo et al. 2005). There are different approaches to analyze the environmental efficiency of a firm. Those may include reducing the environmental impact while keeping the inputs and outputs constant, or reducing the environmental impacts and along with increasing of desirable output while keeping the input constant, or reducing the inputs and environmental impacts simultaneously while keeping the output constant (Kuosmanen and Kortelainen 2004). However the disposability assumption of the environmental impact or undesirable output gained a considerable attraction in the literature (Kuosmanen 2005). In crop production process, the farmers' do not have any direct control on the intended output increase because many external factors affect the output therefore following Kuosmanen and Kortelainen (2004), the environmental efficiency has been modelled by reducing the inputs as well as the environmental impacts while keeping the output constant. The efficiency measure can be computed by means of the following equation:

Minimize ϑ

Subject to

$$\vartheta x_j - X\lambda \geq 0 \qquad (Equation\ 3.10)$$

$$Y\lambda \geq y_j$$

$$B\lambda = \vartheta b_j$$

$$\sum \lambda_j = \vartheta$$

$$\lambda \geq 0\ and\ \ 0 \leq \vartheta \leq 1$$

where $'\vartheta'$ is a scalar and its value is the environmental efficiency value of the 'j^{th}' farm and 'λ' is the intensity vector of the weights of efficient DMUs, which helps to project inefficient DMUs to an efficient frontier. 'X','Y' and 'B' represent the input, desirable output and undesirable output matrix of N number of farms, 'x_j' represents the input vector of the j^{th} farm, 'y_j' represents the desirable output vector of j^{th} farm and b_j represents the undesirable output vector of j^{th} farm.

Variables of environmental impact were selected to calculate the environmental efficiency of each cotton cropping system. All but one of the variables were adopted from Picazo-Tadeo et al. (2011), Picazo-Tadeo et al. (2012) and Gómez-Limón et al. (2012). One additional variable, water use, was selected because water use is a very important environmental indicator due to water scarcity in arid Pakistan. To make cumulative environmental impacts on each cropping system, each environmental pressure needs to be assigned a proper weight (Picazo-Tadeo et al. 2011). In this case, the DEA weights were applied to assess the relative environmental efficiency of each cropping system. As per area unit, the environmental impacts incurred by cotton crop are related to the inputs/practices used by the farmers and farming is considered a typical variable return to scale activity therefore variable return to scale model has been employed.

3.9.4 Eco-efficiency analyzes with DEA

Based on the common definition of eco-efficiency as the ratio of economic value added to environmental impacts (OECD, 1998), Thanawong et al. (2014) have assessed the eco-efficiency of rice cropping systems in Thailand. The approach provides a reasonable proxy to sustainability analysis, yet it faces the issue of multiple eco-efficiency ratios or indicators (as many as the environmental impact indicators). In section 3.9.3, it was tried explore the potential of DEA for providing single efficiency scores in cotton cropping systems, based upon a set of farm level ad-hoc environmental impact indicators. Yet, LCA has not been used to generate environmental impact indicators and to assess eco-efficiency.

With the advancement of DEA approach researchers have started handling the environmentally undesirable outputs into their models as a by-product (Zhang et al, 2008; Picazo-Tadeo et al., 2011; Avadí et al., 2014, leading to ecological-economic efficiency, or eco-efficiency. Low eco-efficiency score of any given production system always results from low income and/or high environmental impacts.

The joint application of LCA and DEA (Vázquez-Rowe et al., 2012; Mohammadi et al., 2013) has recently emerged as a way to find out trade-off options between environmental impacts and economic return. This approach also helps to compute the potential reduction of environmental impacts through possible reduction of inputs, towards higher eco-efficiency.

The DEA approach for our study supposes that the value added or net income denoted by variable v, generated in the production processes of a set of j = 1, 2,…, J cropping systems or DMUs. Additionally, the production processes generate a set of n = 1, 2,…, N environmental impacts, which are denoted by p = (p1, p2,…, Pn). Following Kuosmanen and Kortelainen (2005), the production technology is given by:

T = [(v, p): value added v can be generated with environmental impacts p]

To reasonably model the eco-efficiency of the DMU, following Kuosmanen and Kortelainen (2005), Schaffel and La Rovere, (2010), Picazo_Tadeo et al (2011), Gómez-Limón et al (2012), it has been attempted to produce a certain amount of net income with as few environmental impacts as possible. The reference technology can provide all feasible relationships among value added and multiple environmental impacts, and it can be modeled using simultaneously reducing the environmental impacts through resource use and pollutant emissions reduction while maintaining the constant output (Kuosmanen and Kortelainen 2005). The efficiency measure can be computed using the following linear programming model:

Minimize θ

Subject to

$$v_j \leq \sum_{j=1}^{J} \lambda_j v_j$$

$$\theta_j p_{nj} \geq \sum_{j=1}^{J} \lambda_j p_{nj} \qquad (\textit{Equation 3.11})$$

$$\sum \lambda_j = 1$$

$$\lambda \geq 0 \text{ and } 0 \leq \theta \leq 1$$

where θ is a scalar, whose value is the eco-efficiency value of the j^{th} farm, and λ is the intensity vector of the weights of efficient DMUs, which helps to project the inefficient DMUs to an efficiency frontier. v_j represent the value added of j^{th} DMU, , p_{nj} represents the environmental impact of n category of the j^{th} farm.

The environmental impact variables (from LCA) and net income were used to calculate the eco-efficiency of each cotton-cropping system. Following, Picazo-Tadeo et al. (2011) we have avoided the bias of subjective choice of assigning common weights to environmental impacts, and decided DEA aggregation method. As per area unit, the environmental impacts that are incurred by cotton crops are related to the inputs and practices that are used by the farmers, and farming is considered a typical variable return-to-scale activity. Therefore, the VRS model was used.

The environmental efficiency model with farm level ad-hoc environmental impact indicators and eco-efficiency (from LCA) can assess the radial efficiency of each farm and helps to assess the potential equi-proportional reduction of the amount of input variables. Following the methodology developed by Torgersen et al. (1996), the pressure-specific environmental efficiency scores of cotton cropping systems were assessed using equation 6 for each environmental pressure.

$$\text{Impact specific environmental efficiency} = \frac{\vartheta P_{nj} - S_{nj}^{p}}{P_{nj}} \qquad (\textit{Equation 3.12})$$

Where 'P_{nj}' show the impact *'n'* of *'j'* farm and ϑ stands the environmental efficiency. In this frictional equation the numerator indicates total amount of potential impact reduction which consists of radial reduction and slack based reduction of the impact and the denominator indicates the observed or the actual amount of the impact generated by farm *'j'*.

3.10 Identifying the factors affecting efficiency: regression approaches

A regression analysis has been performed in order to investigate the factors that influence the technical, cost and environmental efficiencies of the DMUs. To that aim, a set of socio-economic and technical variables has been selected. In many cases, a Tobit model has been used at the second stage of efficiency analysis, and recently by Mohapatra and Sen (2013), Gómez-Limón et al. (2012) and Wossink and Denaux (2006). Nevertheless considering the recent criticism of potential biasness in the efficiency scores, the bootstrapped efficiencies scores has been used following the method developed by Simar and Wilson (2000) and Simar and Wilson (2007). They emphasized that the efficiency scores generated by DEA are strongly dependent on each other and it might violate the basic assumption of regression model in second stage. Instead, Simar and Wilson (2007) proposed truncated regression and bootstrapping procedure which enables for consistent inferences in the second stage regression. After calculating the bias corrected efficiency score, the following regression model have been used to regress the bias corrected efficiency scores with contextual variables.

$$\hat{\theta} = z_i\beta + \varepsilon_i \qquad (Equation\ 3.13)$$

Where $\hat{\theta}$ represents the efficiency score of each DMU; 'β' represent the vectors of unknown parameters; 'z_i' is the vector of factor which represent the explanatory variables 'i'(i = 1, 2,…,m) and 'ε_i ' is the error term, N(0, σ_ε^2) with left truncation 1- $z_i\beta$. The step-by-step bootstrapping truncated regression is described by Simar and Wilson (2007), Barros and Assaf (2009) and Barros and Barrio (2011) as given below.

The computation of DEA efficiency score θ_i for all 'n' decision making units (DMUs) using Data Envelopment Analysis models discussed above.
The estimation of (equation 3.12) by maximum likelihood, considering it a truncated regression model to provide the maximum likelihood estimates β as $\hat{\beta}$ and σ_ε as $\widehat{\sigma_\varepsilon}$.
For each firm i = 1, …, n looping over the next three steps (3.1 to 3.3) L times in order to obtain the bootstrap estimates.
3.1) For each firm i = 1, …, n draw ε_i from $N(0, \hat{\sigma}_\varepsilon^2)$ distribution with left truncation at $(1 - z_{i\,\hat{\beta}})$.
3.2) For each DMU 'n' computation of $\theta_i^* = z_i\hat{\beta} + \varepsilon_i$.
3.3) Used the maximum likelihood to estimate truncated regression of θ_i^* on z_i yielding the required estimates i.e. $(\hat{\beta}^*, \hat{\sigma}_\varepsilon^*)$.

Table 3.4 explains the variables used in second stage truncated regression analysis. Farmers' educational level, age of the farm operators, size of farm, access to leased land and owned land, sowing method and exposure to extension education and trainings are the variables that were regressed against technical-, cost- and environmental efficiency scores of the DMUs in order to see if these socio-economic and technical variables had any effect on the efficiency of the farms.

Table 3.7 Description of the variables used in second stage truncated regression

Variables	Description
Field characteristics	
Medium farm	1 for medium sized farm and 0 otherwise
Large farm	1 for large sized farm and 0 otherwise
Sowing method	1 for raised bed sowing and 0 for flatbed sowing method
Land tenure	1 for renter operator and 0 for owner operator
Education and age	
High School	1 for high school and 0 otherwise
Beyond high School	1 for beyond high school and 0 otherwise
Age (years)	age in years of the farm's operator
Exposure to extension and training	1 for interaction with extension agent and 0 for no interaction with extension agent

Chapter 4

Description of Typical Cotton Cropping Systems: Technical Performances and Efficiency Analysis

This chapter discusses the technical and economic performances of cotton cropping systems and presents the empirical results of the efficiencies of these domains. The analysis of technical and economic efficiencies of each DMU in the diverse cropping system was carried out using the Data Envelopment Analysis (DEA) approach as explained in chapter 3. Mean values of these efficiencies were compared among the systems. Following the calculation of technical and economic efficiencies, the determinants of efficiency were estimated through truncated regression analysis, and its empirical results are discussed here.

4.1. Cotton cropping systems: introduction

Cotton is grown under irrigated conditions throughout Punjab. The amount of inputs used varies from farm to farm depending upon various factors. The most common practice of cotton cultivation is cotton-wheat-cotton rotation. The duration of one cotton crop, from land preparation until picking, lasts approximately six to seven months. Cotton is grown both on raised seedbeds (ridges) and on flat seedbeds depending on farmers' decisions which is influenced by the availability of resources and sowing time. Manually the seed is sown on the ridges but drill sowing is generally performed on the flat seedbed.

4.2 Variable inputs in cotton production

The major variable inputs of cotton crop production are: human labor, machinery, water used for irrigation, seed, chemical fertilizers and pesticides. Cotton is a labor intensive crop and human labor is involved from land preparation to picking. The most important activities of human labor are: sowing, thinning, weeding, and picking. Sowing is manually performed in the case of the raised seedbed sowing technique; however in the case of the flat seedbed sowing system, mechanical sowing is applied which is commonly known as drill sowing. Thinning is an essential phase executed a few days after plant germination and is performed manually, in order to maintain a specific distance between the remaining plants to allow them to grow in a healthier way. Manual weeding is performed but it depends on the decision of farmers and the availability of resources. Generally, fertilizers are applied manually but pesticide applications are performed both manually and mechanically. In Pakistan, the entire picking of cotton crop is manually performed and no mechanical picking prevails in the country.

Land preparation (deep ploughing, rotary tillage, leveling and seedbed preparation) is performed mechanically either by owned farm machinery or hired machinery depending on its availability. Mostly small and resource poor farmers do not have their own machinery and therefore they have to hire machinery from the neighboring farmers and to pay rent to those farmers. All farmers in the selected area apply chemical fertilizers and pesticides but its doses and types vary from farm to farm. The most common fertilizers are Urea and Diammonium Phosphate (DAP). Beside these fertilizers, Single Super Phosphate (SSP), Triple Super Phosphate (TSP), Ammonium Nitrate and Potassium Sulphate are also applied. Cotton is susceptible to insect pest attacks and the main components of pesticides are insecticides and herbicides. Some farmers treat the cotton seed prior to sowing with some chemicals in order to avoid insect pest attack in in early growth stage. Herbicides are also sprayed prior to the germination of the seed to avoid weed growth in early stage. Unwanted weeds always compete with cotton plant at early growth stage which can hinder the plant growth and ultimately affect the yield. Variable inputs are used depending upon the farmers' decision and ultimately it affects the cost of production, yield and income of the farmers.

Keeping in view the variation of input used and output obtained due to different management practices, cropping systems were classified into small, medium and large farms. Table 4.1 presents the descriptive statistics for the input variables used in cotton production.

Table 4.1 Sample description of the input variables used by different farm size categories (mean, standard deviation)

Variables	Farm Categories						
	Small farms		Medium farms		Large farms		Differences among groups
	Mean	SD	Mean	SD	Mean	SD	
Water use (m^3/ha)	**9220.80**	2461.2	**9345.10**	1902.8	**8674.20**	1969.9	($^{\times\times}$)
Seed rate (kg/ha)	**22.73**	4.9	**23.80**	5.9	**25.57**	5.0	($^{+++}$), ($^{\times\times}$)
Labor (man-hours/ha)	**738.8**	403.4	**790.1**	284.7	**709.85**	368.5	(**), ($^{\times\times\times}$)
Fuel (litre/ha)	**107.33**	31.8	**128.7**	43.07	**138.90**	48.0	(***), ($^{+++}$)
Nitrogen (kg/ha)	**259.1**	109.9	**284.0**	114.0	**271.95**	95.9	(**)
Phosphorus (kg/ha)	**52.55**	38.0	**42.72**	27.3	**43.67**	31.2	
Pesticides (g/ha)	**5679.9**	3138.7	**7651.4**	2992.6	**7454.60**	2755.0	(***), ($^{+++}$)
Yield (kg/ha)	**2004.7**	1486.8	**2177.5**	999.4	**1996.50**	1197.9	(***), ($^{\times\times}$)
Net income (US$/ha)	**1125.9**	1171.8	**1252.6**	869.3	**1127.90**	1034.2	(*), ($^{\times}$)
No. of observations (n = 169)	40		68		61		

Symbols after groups indicate differences between:

a) Small farms and medium farms at (* = Significance level $p \leq 0.10$, ** = Significance level $p \leq 0.05$, *** = Significance level $p \leq 0.01$)
b) Small farms and large farms at ($^{+}$ = Significance level $p \leq 0.10$, $^{++}$ = Significance level $p \leq 0.05$, $^{+++}$ = Significance level $p \leq 0.01$)
c) Medium farms and large farms at ($^{\times}$ = Significance level $p \leq 0.10$, $^{\times\times}$ = Significance level $p \leq 0.05$, $^{\times\times\times}$ = Significance level $p \leq 0.01$)

The Mann-Whitney U-Test (two-sided) was used to test whether the differences of input among different farm sizes were significant. A comparison of small farms with medium farms showed that labor hours, fuel, nitrogen fertilizers and pesticides doses were significantly different between small and medium farms. It was observed that small farmers used lesser labor hours, fuel, nitrogen fertilizers and pesticides compared to medium farms. Similarly, a comparison of small farms with large farms showed that seed rate, fuel consumption and pesticides doses were significantly different between small and large farms, and small farms were using fewer amounts of these inputs as compared to large farms. Again, a comparison of medium farms with large farms showed that water, seed and labor inputs were significantly different between medium and large farms. Medium farmers applied more water and labor compared to large farmers. However, the seed rate of large farmers was higher than medium farmers. Overall, medium farms were using more inputs per unit area as compared to small farms and large farms. Similarly, a yield comparison between the categories showed that the average yield of seed cotton of small farms was 1998.2 (±1450.5) kilograms per hectare, medium farms 2186.9 (±1013.0) kilograms per hectare, and large farms 1996.5 (±1197.9) kilograms per hectare. Medium farms were producing a significantly higher amount as compared to small and large farms. However small and large farms are not significantly different.

4.3 Profitability of cotton production

Table 4.2 presents an analysis of the economic performance of sampled farms. The percentage contributions of each input cost were analyzed separately and are shown in figure 4.1. The contribution of material inputs such as fuel, chemical fertilizers and pesticides to the total variable cost of the inputs was 72.83 percent, 73.22 percent and 74.68 percent for small, medium and large farms respectively. It indicates that the larger farms spent more on material inputs than small farms. In the case of small farms, the contribution of chemical fertilizers and pesticides was 40.32 percent, for medium farms, 42.94 percent, and for large farms, 44.17 percent. This shows that large farms were using higher doses of chemicals fertilizers and pesticides, medium farms were using lower doses, and small farms were using the least chemical inputs. Costs related to non-renewable energy consumption were observed to be the second largest contributor to the total variable input cost, and consisted of fuel consumption for land preparation and cultural management practices as well as electricity consumption for the pumping of irrigation water. The contribution of non-renewable energy cost to the total cost for small farms was estimated to be 32.32 percent, for medium farms, 30.28 percent and for large farms, 30.51. This difference is probably because of the economies of scale of different farm sizes.

Table 4.2 Sample description of the cost of input variables used by different farm categories (mean, standard deviation and percentage contribution of each input to the total cost)

Variables	Farm Categories								
	Small Farms			Medium Farms			Large Farms		
Cost of inputs (US$/ha)	Mean	SD	% of total cost	Mean	SD	% of total cost	Mean	SD	% of total cost
Water	**173.25**	99.29	19.38	**169.18**	67.54	17.45	**148.12**	53.9	16.36
Seed	**45.41**	15.63	5.08	**43.31**	22.79	4.47	**48.92**	38.79	5.40
Labor	**199.23**	102.68	22.29	**216.22**	86.29	22.31	**180.3**	111.21	19.92
Fuel	**115.63**	37.3	12.94	**124.29**	38.37	12.82	**128.04**	44	14.14
Nitrogen	**101.77**	45.04	11.39	**111.71**	49.15	11.52	**103.21**	45.2	11.40
Phosphorous	**150.12**	119.25	16.80	**186.21**	97.35	19.21	**183.07**	102.63	20.22
Pesticides	**108.41**	57.83	12.13	**118.3**	56.61	12.20	**113.51**	40.53	12.54
Total cost/ ha	**893.82**	376.42		**969.22**	258.09		**905.17**	296.78	
Net income/ha	**1125.9**	1131.26		**1252.6**	869.3		**1127.9**	1034.2	
No. of observations	40			68			61		

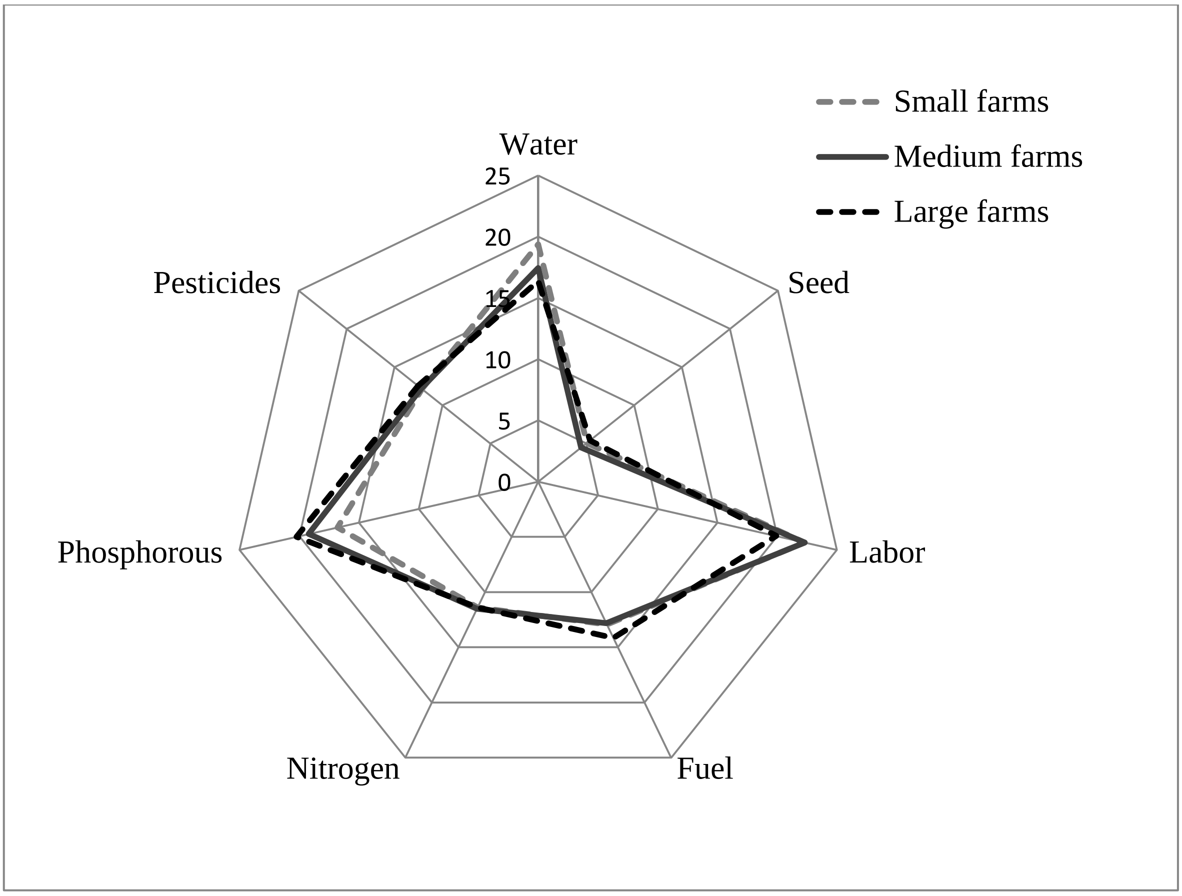


Figure 4.1 Percentage cost contribution of variable inputs to the total variable cost as per farm size

Profit or net income of each farm category was calculated based on the cost of variable inputs and income from seed cotton at farm gate. Analyzing individual inputs quantity and cost shows a significant variation of input and cost among farms groups. Comparing seed cost it was observed that most of the medium farms were using their own farm seed and were experiencing less cost, while small farmers and large farmers were buying seed form the market at higher prices, because small and large categories of farm sale out their produce at the time of harvest due to different reason. Being economically well-off, large farmers were intended to use good quality of seed supplied by different companies. However, small farmers are normally under informal debt of the local agricultural input dealers during crop growth period and they have to pay-off their loan and are forced to sale out the produce at the time of harvest. Comparing labor hours and cost among different categories of farm shows that less labor hours was required by small farms because family labor of small farms efficiently works at farm. Mostly in medium farms manual cultural management practices such as weeding were performed and more labor hours per hectare were required and thus higher cost of labor incurred by medium farms. Large farmers were intended to use mechanical weeding and therefore less labor hours and cost and higher fuel consumption and thus cost incurred by large farms. Comparing chemical fertilizers, small farms were using less nitrogen fertilizers compared to medium and large farms and therefore less cost incurred by small farms. In contrast, small farms were using highest amount of phosphorus fertilizers with least cost. There reason behind this fact is that the small farms were using phosphorus fertilizers such as SSP and TSP with less cost while medium farms and large farms were using DAP which costs higher.

4.4 Techno-economic performance indicators of cotton production

Table 4.3 presents the inputs productivities of each farm size category. Input productivity indicators refer to the amount of output produced as per unit of given inputs. These indicators are calculated based on the inputs data, yield and farm gate prices of output. Using these indicators, the differences in input used by different farm groups was analyzed. Comparing the productivities among different farm groups, again, the Mann-Whitney U-Test (two-sided) was used to test whether the differences in productivities among different farm sizes were significant. A comparison of the water productivity indicator among farm groups indicated that water productivity of large farms was significantly higher as compared to medium farms, whereas no significant differences were observed between small and medium farms and between small and large farms. This indicates that large farms were using lower volumes of water as compared to medium farms. It is also clear from table 4.1 that large farms were using significantly lower volumes of water per hectare as compared to medium farms. Results from the energy productivity indicator showed that small farms were using significantly lesser energy than medium farms. No significant difference was observed in fertilizer productivity across all three categories of the farms.

Pesticide productivity of small farms was significantly higher as compared to medium and large sized farms. Significantly higher pesticide productivity between small and medium farms and between small and large farms indicates that small farms were applying pesticides doses in an effective and timely manner keeping in view insect pest outbreak. It can be assumed that medium and large farms were applying higher doses of pesticides uniformly across their fields without keeping in view the insect pest spots. Labor productivity of small and large farms was significantly higher as compared to medium sized farms. The lower labor productivity of medium sized farms indicates the overemployment of human labor by medium sized farms. Higher energy and labor productivity between small and medium farms indicates that small farms were efficiently using these resources. The benefit-cost ratio of small farms was significantly higher as compared to medium farms at 5 % level of confidence. Similarly, the benefit cost ratio of large farms was higher as compared to medium farms at 10% level of confidence.

Comparing the productivities among different farm groups it has been observed that large farms were more productive while medium farm showed lowest productivities in all compartments. Pesticides productivity of small farms was highest because of the timely application of pesticides by small farms. Small farms are less intensified and because of the economies of scale, the factors of productivities of small farm are less compared to large farms. Productivities of different inputs of medium farms are less because they intended to get higher yield with higher level of inputs but without meeting efficient input mix it’s difficult to achieve higher levels of productivities. The productivities of large farms is higher because the economies of scale and proper utilization of inputs. Individual inputs productivity may not address the overall farm efficiency and therefore the efficiency analysis has been performed in next section.

Table 4.3 Sample description of techno-economic indicators as per farm sized category (mean, standard deviation)

Variables	units	Farm categories: Small farms Mean	SD	Medium farms Mean	SD	Large farms Mean	SD	Differences among groups
Water productivity	Kg/m^3	**0.259**	0.112	**0.243**	0.098	**0.333**	0.209	($^{\times\times}$)
Energy productivity	Kg/ MJ	**0.088**	0.031	**0.080**	0.042	**0.101**	0.068	(**)
Fertilizers productivity	Kg/nutrients	**6.893**	2.909	**6.684**	3.691	**8.472**	5.639	
Pesticides productivity	Kg/active ingredients	**0.518**	0.276	**0.386**	0.392	**0.426**	0.305	(***), ($^{++}$)
Labor productivity	Kg/ man hour	**3.370**	1.151	**3.009**	1.520	**4.690**	3.769	(**), ($^{\times\times\times}$)
Benefit/cost ratio		**1.662**	0.745	**1.399**	1.176	**2.438**	2.578	(***), ($^{\times}$)
No. of observations N = 169		40		68		61		

Symbols after groups indicate differences between:

a) Small farms and medium farms at (* = Significance level $p \leq 0.10$, ** = Significance level $p \leq 0.05$, *** = Significance level $p \leq 0.01$)
b) Small farms and large farms at ($^{+}$ = Significance level $p \leq 0.10$, $^{++}$ = Significance level $p \leq 0.05$, $^{+++}$ = Significance level $p \leq 0.01$)
c) Medium farms and large farms at ($^{\times}$ = Significance level $p \leq 0.10$, $^{\times\times}$ = Significance level $p \leq 0.05$, $^{\times\times\times}$ = Significance level $p \leq 0.01$)

4.5 Computing variables for efficiency analysis

The data from tables 4.1 and 4.2 in the previous section presents the descriptive statistics of the variables used in the efficiency analysis. The input-oriented radial efficiencies for each farm have been computed using data envelopment analysis (DEA), which calculates the proportional reduction of each input while maintaining the output level. This radial reduction helps to analyze the potential reduction of inputs and the potential profitability of the farms that can be generated without compromising output level.

Agronomic management practices and resources have a synergistic effect on cotton crop yield and the environment. Resource use intensification depends on the availability of resources and the financial status of each farmer. Generally, small-scale farmers have fewer resources available, due to a weak financial position and less access to credit, which make them unable to purchase inputs, which in turn leads to lower land productivity (Fan and Chan-Kang, 2005). The frequency distribution of yield per farm size (Figure 4.2), frequency distribution of irrigation water use (Figure 4.3), frequency distribution of active ingredients in pesticides (Figure 4.4), frequency distribution of energy use (Figure 4.5), frequency distribution of chemical fertilizers application (Figure 4.6) and frequency distribution of labor hours (Figure 4.7) shows the range of inputs as well as the diversity of farm inputs and outputs in Punjab, Pakistan. The empirical results from the efficiency analysis can help to investigate a potential improvement in input savings. The observed diversity follow approximately a normal distribution. Overall, these figures highlight a lower use of inputs by smaller farms.

Figure 4.2 Frequency distribution of yield/ha per different farm categories

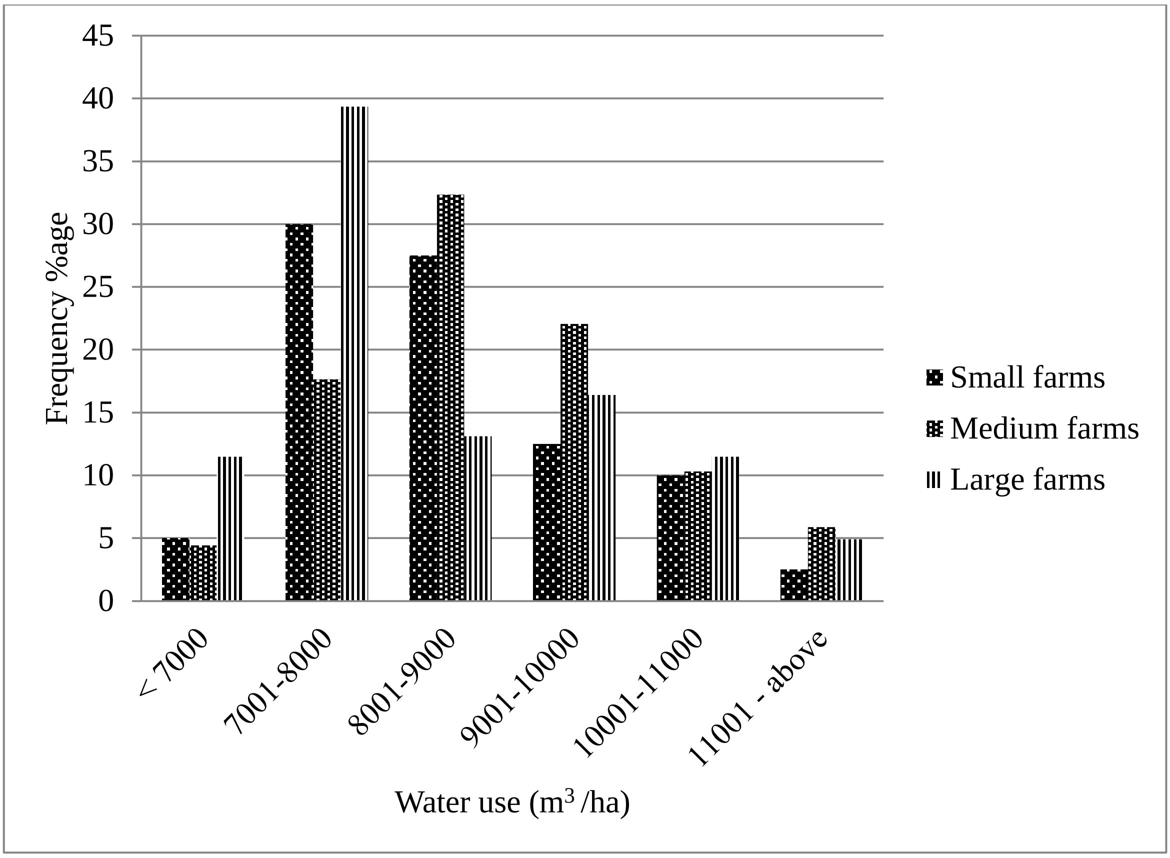


Figure 4.3 Frequency distribution of irrigation water use (m^3/ha) of each farm category

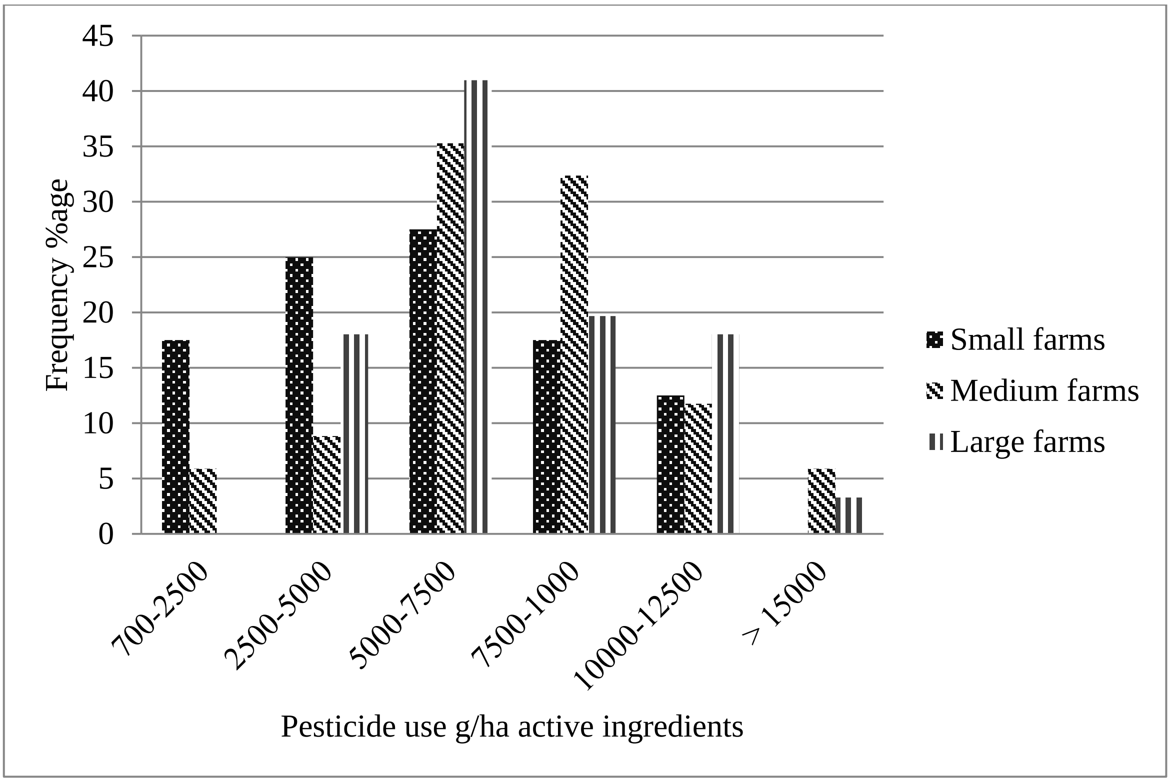


Figure 4.4 Frequency distribution of the active ingredients in the pesticides used (g/ha)

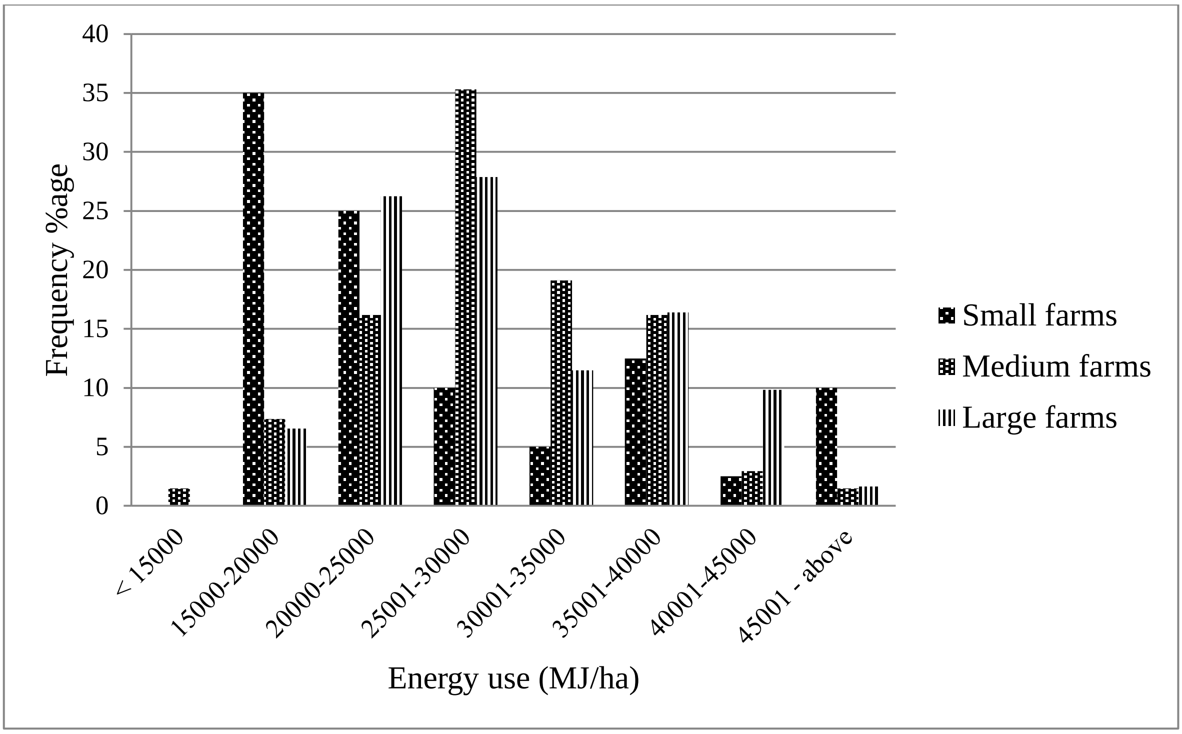


Figure 4.5 Frequency distribution of energy use (MJ/ha)

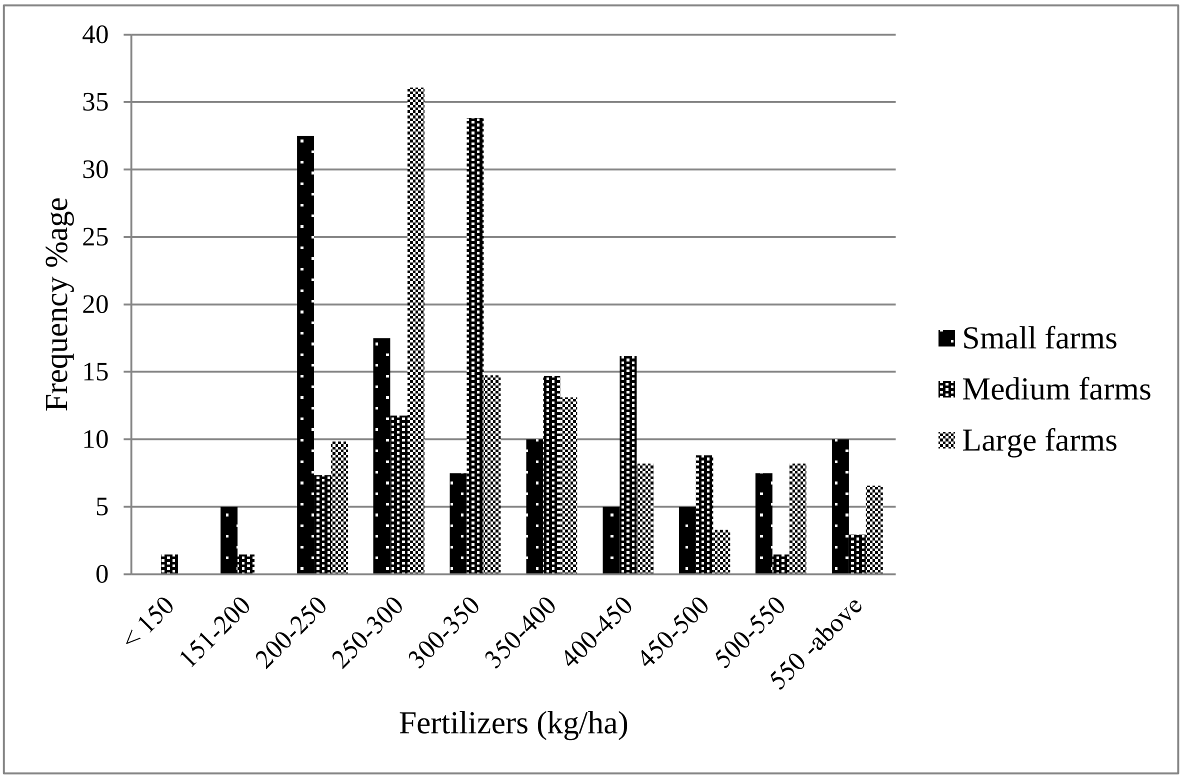


Figure 4.6 Frequency distribution of fertilizers application (kg/ha)

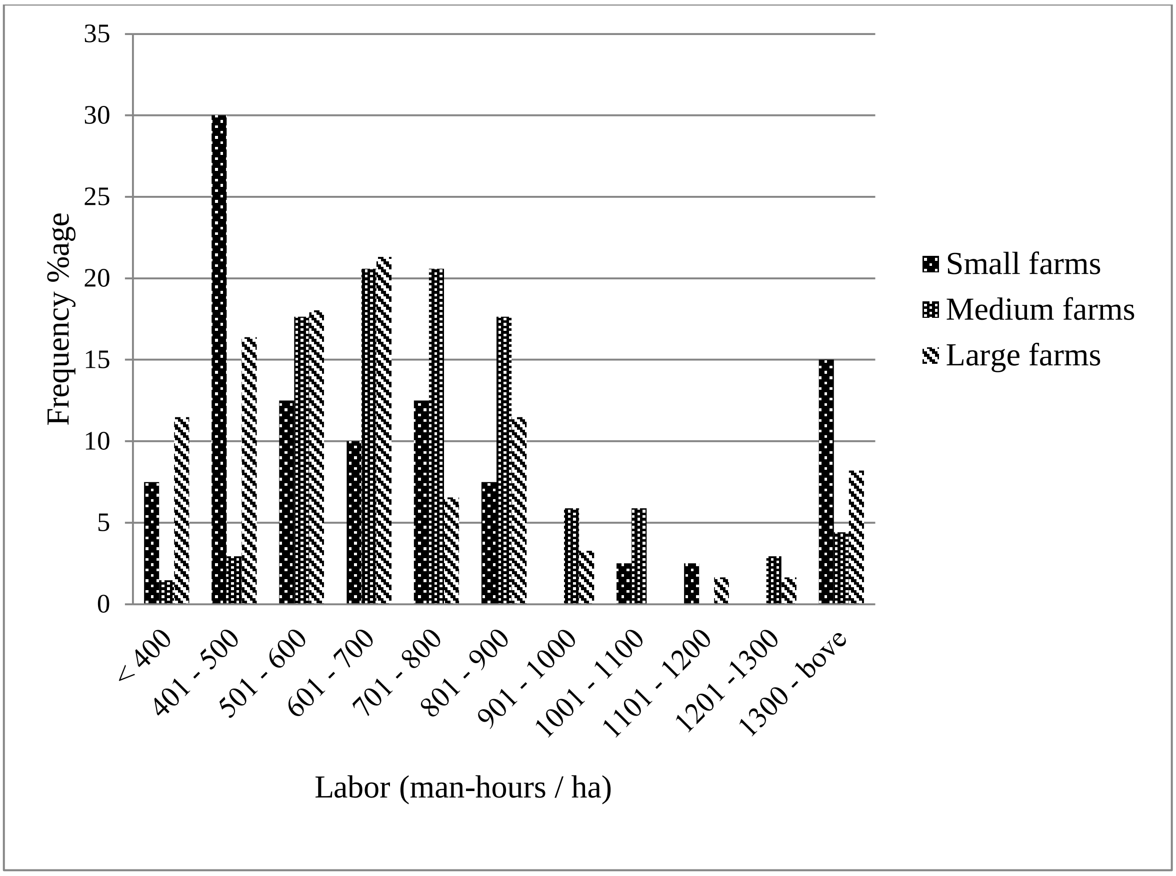


Figure 4.7 Frequency distribution of labor hours (man-hours/ha)

4.6 Efficiency analysis

Table 5.4 summarises the results of the efficiency analysis using DEA. The analysis showed that the mean pure technical efficiency TE_{BCC} of the small farms was the highest, which means that the small farms made better use of the inputs and resources than medium and large farms. Similarly, the mean cost efficiency of the small farms was the highest followed by large farms, and the lowest cost efficiency was found in the medium-sized farms. The Mann-Whitney U-test (two sided) was used to test whether the differences in efficiencies of different farm sizes were significant. Assuming a constant return to scale (CRS), the technical efficiencies of different farm sizes were not significantly different. Assuming variable returns to scale (VRS), the technical efficiencies between small and medium and between small and large farm sizes were significantly different at 5% confidence level. Cost efficiency differences between small and medium farms were also found significantly different at 5% confidence level. Significant differences were also found between small and medium farmers in the cost allocative efficiency (CAE) and scale efficiency (SE) analyzes at 10% confidence level. Similarly, no significant difference was found between medium and large farmers. A statistically significant difference between the efficiencies of farm sizes was observed using a VRS which indicates that these farmers are technically operating at an efficient level but their small output levels with given inputs are significantly different. It has been confirmed by comparing technical efficiency coefficients using the CRS and NIRS for the inefficient DMUs. All of the inefficient farmers exhibited increasing returns to scale, which means that they can reduce their inputs without compromising the given income level or produce more seed cotton, thus increasing their income level within the given input mix.

An increasing trend in using fuel and other agrochemicals was observed from the small- to medium-sized farms and from the medium to large farms, indicating that the small farms tended to have lower costs compared to medium and large farms. The Spearman's rho correlation coefficients (r) between cost efficiency and TE_{BCC} was 0.684 and the Spearman's rho correlation coefficients (r) between cost efficiency and cost allocative efficiency was 0.935 (see Appendix A), indicating that there is a direct linear relationship between cost efficiency, pure technical efficiency, and between cost efficiency and cost allocative efficiency.

Table 4.4 Technical and cost efficiency analysis, per farm size

Efficiency	Small Farms		Medium Farms		Large Farms		
	Mean	SD	Mean	SD	Mean	SD	*P<0.05*
TE_{BCC} [a]	**0.958**	0.065	**0.917**	0.082	**0.911**	0.097	0.019**
TE_{CCR} [b]	**0.539**	0.236	**0.586**	0.234	**0.539**	0.206	0.374
CE [c]	**0.842**	0.174	**0.767**	0.165	**0.799**	0.180	0.075
CAE [d]	**0.878**	0.169	**0.833**	0.141	**0.872**	0.158	0.191
SE [e]	**0.564**	0.245	**0.631**	0.223	**0.590**	0.207	0.224

[a]Total technical efficiency, [b] Pure technical efficiency, [c] Cost efficiency, [d] Cost allocative efficiency, [e] Scale efficiency

The frequency distribution of technical efficiency in table 4.5 indicates that the majority of DMUs were inefficient. The percentage of efficient DMUs using a constant return to scale model (CCR) was found to be 5%, 8.82% and 6.56% of small, medium and large farms, respectively. Nevertheless the number of efficient DMUs increased when variable return to scale model (VRS) has been employed. The highest percentage of the DMUs at BCC-efficient frontier was observed in the small farms (45%) followed by large (28%) and medium (21%) farms. The greatest increase of the efficient DMUs at BCC-efficient frontier indicated the highest scale inefficiency, meaning that these DMUs are not using inputs with an optimal mix and the level of scale inefficiencies can help to adjust the scale size. Inadequate timing of using different inputs in crop production can also cause scale inefficiencies. From the scale inefficiency, the extent to which resources can be saved and the adjustment of the scale size for optimal production may be inferred. The BCC-inefficient farms had technological and allocative inefficiencies, means that they used an inappropriate amount of different input and deviated from the most productive scale size (MPSS) (Banker 1984). From the mean scale efficiency analysis, the highest scale efficiency was observed in medium farms followed by large farms and small farms.

Table 4.5 Frequency distribution for technical, pure technical and cost efficiency as per farm category

CCR Model	Small Farms	%	Medium Farms	%	Large Farms	%
< 60%	27	67.50	40	58.82	38	62.30
60-70%	3	7.50	9	13.24	8	13.11
70-80%	3	7.50	7	10.29	10	16.39
80-90%	1	2.50	1	1.47	0	0.00
> 90%	4	10.00	5	7.35	1	1.64
Efficient	2	5.00	6	8.82	4	6.56
Number of farmers	40		68		61	
Mean efficiency score	0.539		0.585		0.539	

BCC Model						
< 60%	0	0.00	0	0.00	0	0.00
60-70%	0	0.00	0	0.00	1	1.64
70-80%	2	5.00	8	11.76	7	11.48
80-90%	4	10.00	19	27.94	14	22.95
> 90%	14	35.00	21	30.88	18	29.51
Efficient	20	50.00	20	29.41	21	34.43
Number of farmers	40		68		61	
Mean efficiency score	0.957		0.916		0.911	

Cost efficiency						
< 60%	6	15.00	12	17.65	9	14.75
60-70%	2	5.00	12	17.65	12	19.67
70-80%	7	17.50	19	27.94	10	16.39
80-90%	5	12.50	8	11.76	7	11.48
> 90%	5	12.50	1	1.47	2	3.28
Efficient	15	37.50	16	23.53	21	34.43
Number of farmers	40		68		61	
Mean efficiency score	0.841		0.767		0.798	

4.7 Determinant of efficiency analysis

Table 5.6 shows the bootstrapped left truncated regression results of the technical- and cost efficiency at variable return to scale (appendix B–1 and appendix B–2) of the selected DMUs. The number of bootstrap replications has been set 2000 following Afonso and St. Aubyn (2006) and Barros and Assaf (2009). The estimated coefficients of the factors that affect different efficiencies of the DMUs are given in the table. In some cases different selected factors affect significantly on technical-and cost efficiency of the DMUs such as the farm size, raised-bed sowing, education level and exposure to extension trainings. Farmers prefer to grow cotton on the raised- seedbed in order to avoid damages occurs due to rainfall if it happens in early stages of crop growth and to save irrigation water which ultimately needs extra management activities. It was observed that the raised-bed sowing have a statistically significant effect on the technical efficiency of the DMUs and which suggests that the increased use of mechanical and other management practices cause technical inefficiency of the farms. Paradoxically, higher education level relates significantly to technical- and cost inefficiency of the farms, which finding deviates from the usual assumption that higher education can leads to higher efficiency. It is plausible that educated farmers' higher awareness and knowledge of the importance of agrochemicals plays as a negative factor in the sense that they tend to overdose on agrochemical application, which is also made possible by their relatively better-off financial status. In other words, they tend to extensify (use more inputs) instead of intensify production (be more efficient). Finally, high exposure to extension services and trainings significantly relates to high technical efficiency.

Table. 4.6 Truncated bootstrap regression estimates

Explanatory variables	Explained variable			
	Technical efficiency		Cost efficiency	
	Coeff.	p-value	Coeff.	p-value
Medium farms	- 0.0290	0.083*	- 0.0516	0.051*
Large farms	- 0.0222	0.267	- 0.0162	0.588
Sowing method	- 0.0267	0.034**	- 0.0386	0.035**
Land tenure	0.0028	0.879	0.0192	0.493
High school	- 0.0116	0.525	- 0.0480	0.088*
Beyond High School	- 0.0263	0.066*	- 0.0453	0.051*
Age	- 0.0008	0.251	0.0004	0.624
Exposure to extension trainings	0.0326	0.026**	0.0322	0.123
Constant	0.9153	0.000***	0.8801	0.000***
Sigma	0.0807	0.000***	0.1210	0.000***
Wald chi2 (p-value)	30.510	0.0002***	15.390	0.052*

* = Significance level $p \le 0.10$
** = Significance level $p \le 0.05$
*** = Significance level $p \le 0.01$

4.8 Summary

In this chapter the input productivities and the efficiency of different farm categories has been computed and compared. It has been observed that the input productivities of large farms were highest followed by small and medium farms. On the other hand the technical and cost efficiency of small farms was highest followed by large and medium farms. Medium farmers were using higher level of inputs and were getting higher yield but due to higher cost of inputs the net income of medium farm was least.

Measuring the efficiencies of cotton farming systems allow for determination of the heterogeneity in efficiency, the level of reduction in the inputs, while sustaining economic return. The analysis also identifies areas of intervention to improve the efficiencies. Improvement in the TE was found to help reduce the cost performance of the studied farming systems. The results also indicate that there is a substantial opportunity to manage the inputs properly to get a better economic return with less cost. Also, the medium farms are operating at the highest scale efficiency level compared to the small and large farms, which means that medium farms are operating at a near efficient scale size. The scale here refers to the use of variable inputs in cotton production and thus not to optimal farm size.

The results of second stage bootstrapped truncated regression analysis allow identifying certain socio-economic causes, on empirical bases. Paradoxically, farmers' formal education level has a negative significant effect on technical- and cost efficiency level. However, the efficiency levels can possibly be increased by providing them with extension and training. Varying levels of inputs create different levels of environmental impacts and those impacts are discussed in next chapters.

Chapter 5

Farm-Level Environmental Impacts of Cotton Cropping Systems

This chapter includes the environmental performance analysis of cotton cropping systems based on based on farm level ad-hoc environmental impacts indicators. Documenting environmental impacts through LCA based environmental impact indicators may prove cumbersome and difficult for managers and practitioners. So these indicators have been developed in order facilitate managers and practitioners to check whether an alternative approach could help. Environmental performance of each DMU from each cropping system has been computed. Mean values of the impact indicators has been compared among different farm categories. The physical quantities of the inputs and their respective environmental impacts have been observed among different farm categories.

5.1 Computing ad-hoc Environmental Indicators

The ad-hoc farm-level environmental impact indicators have been calculated with the help of the methods explained earlier in the chapter of methodology. All these environmental impacts indicators have been analyzed based on per hectare input use. The mean values of ad-hoc environmental impact indicators of each farm category are given in table 5.1.

Table 5.1 Computing environmental performance based on ad-hoc indicators (mean, standard deviation)

Variables	Farm Categories					
	Small Farms		Medium Farms		Large Farms	
	Mean	SD	Mean	SD	Mean	SD
Environmental detrimental effects						
Water use (m^3/ha)	**9220.8**	2461.2	**9345.11**	1902.8	**8674.2**	1969.9
Energy ratio	**0.298**	0.087	**0.299**	0.139	**0.315**	0.121
Nitrogen balance (kg/ha)	**213.29**	87.52	**235.27**	102.57	**226.42**	79.34
Phosphorus balance (kg/ha)	**37.45**	34.09	**26.84**	22.24	**29.15**	25.22
Pesticide risk (kg rats/ ha)	**43869.2**	51619.3	**62898.4**	53489.0	**60717.9**	51167.9
Yield (kg/ha)	**1998.2**	1450.5	**2186.9**	1013.0	**1996.5**	1197.9
Net income (US$/ha)	**1125.9**	1171.8	**1252.6**	869.3	**1127.9**	1034.2
No. of observations N = 169	40		68		61	

5.2 Environmental efficiency

The EE scores for all farm categories were estimated. We used all growers as a reference to calculate the EE assuming a CRS, VRS and NIRS. Using the CCR, only 9 DMUs were operating at an efficient level (i.e., only 5.32% had an EE coefficient of 1.0, which implied that no other cotton grower was more efficient in producing a given level of income with the same environmental impact). Using the VRS, the number of efficient DMUs increased to 50, which showed that 41 more farmers were technically operating at an environmentally efficient level, but they are producing inefficiently small output levels with the given environmental impacts. This result is confirmed by comparing the EE coefficients using the CRS and NIRS for the inefficient DMUs; all inefficient farmers exhibited increasing returns to scale, which indicates that they can reduce their inputs and ultimately their environmental impacts without compromising the given income level or produce more seed cotton, which increases their income level for the given input mix.

Table 5.2 Radial- and pressure-specific environmental efficiencies

	Small Farms		Medium Farms		Large Farms		
	Mean	SD	Mean	SD	Mean	SD	*P<0.05*
Radial efficiency	**0.931**	0.106	**0.874**	0.106	**0.896**	0.107	0.004***
Pressure specific environmental efficiency							
Water use	**0.907**	0.134	**0.850**	0.120	**0.880**	0.118	0.000***
Energy Ratio	**0.865**	0.164	**0.804**	0.188	**0.804**	0.171	0.293
Nitrogen Balance	**0.837**	0.208	**0.735**	0.193	**0.764**	0.196	0.006***
Phosphorus balance	**0.804**	0.251	**0.709**	0.257	**0.751**	0.239	0.076*
Pesticide Risk	**0.894**	0.160	**0.662**	0.290	**0.746**	0.278	0.000***

* = Significance level $p \leq 0.10$
** = Significance level $p \leq 0.05$
*** = Significance level $p \leq 0.01$

Table 5.2 shows the mean value of the overall EE score and pressure-specific EE score for the sampled DMUs, which were calculated using the DEA model that was described in equation 5. The mean radial EE values suggest that the small, medium and large farms can equi-proportionally reduce their environmental pressure by 9%, 13% and 11%, respectively. However, after incorporating the impact-specific slack for each environmental impact, the impact-specific EE was calculated, and further reduction of the environmental pressure was possible without compromising the income level. For small farms, the highest pressure-specific EE was observed in the phosphorus balance, where the maximum attainable reduction was 20%, followed by the nitrogen balance, where the maximum attainable reduction was 17%. For medium and large farms, these groups of farmers were responsible for contributing a high pesticide impact to the environment and creating a more toxic effect possibly because these farmers were using high doses of pesticides or pesticides with high lethality. The Mann-Whitney U-test was again applied to the efficiency indices (i.e., the radial- and impact-specific EE) to determine whether the efficiencies of different farm categories were significantly different. The radial EE and impact-specific EE of the pesticide risk were significantly different at the 5% confidence level between small and medium farms and between small and large farms. The impact-specific EE of water use, nitrogen balance and phosphorus balance between small and medium farms were also significantly different at the 5% confidence level. The energy ratio between small and medium farms and the nitrogen balance between small and large farms were also significant at the 10% confidence level. In contrast, no significant difference was found between medium and large farms.

Table 5.3 Target quantities and potential reduction of environmental impacts

		Water use (m^3/ha)	Energy ratio	Nitrogen (Kg/ha)	Phosphorus (Kg/ha)	Pesticide Risk (Kg rat/ha)
Small farms	Observed quantity	9272.44	0.30	214.14	36.95	40615.10
	Target quantity	8410.10	0.26	179.23	29.71	36309.90
	Difference (%)	-9.30	-13.50	-16.30	-19.60	-10.60
Medium farms	Observed quantity	9311.06	0.30	234.12	27.45	64252.89
	Target quantity	7914.40	0.24	172.08	19.46	42535.41
	Difference (%)	-15.00	-19.60	-26.50	-29.10	-33.80
Large farms	Observed quantity	8674.16	0.32	226.42	29.15	60717.95
	Target quantity	7633.26	0.26	172.98	21.89	45295.59
	Difference (%)	-12.00	-19.60	-23.60	-24.90	-25.40

Table 5.3 indicates the potential reduction in actual and percentage form of the environmental impacts for each farm category. To illustrate the sources of environmental inefficiency in small farms, the potential saving was 862.34 m^3 ha^{-1} for irrigation water, 34.91 kg ha^{-1} for nitrogen fertilizers and 7.24 kg ha^{-1} for P_2O_5, and the energy-input-to-energy-output ratio reduced by 13.5%. Similarly, 22.77% of the toxic effect of the pesticide use can be saved if the farmers reduced the quantity of pesticides used to an optimal level or substituted them with a less lethal product.

The environmental inefficiency can be explained using the technical inefficiency as discussed by Picazo-Tadeo et al. (2011) and Picazo-Tadeo et al. (2012). The TE was measured to understand the extent of environmental inefficiency that may be caused by inefficient management of cotton-farming systems. The Spearman's rho correlation coefficients among the TE_{CCR} and TE_{BCC}, CE, AE, radial EE and impact-specific EE were analyzed. The Spearman's rho correlation coefficient was used to see the relationship among different efficiency measures in the sustainability perspective. The Spearman's rho correlation usually suggested an abnormally distributed efficiency score; to avoid such a misleading correlation, Spearman's rho was selected. The Spearman's rho correlation coefficient (r) (see Appendix A) between TE_{BCC} and EE was 0.800. In addition, the Spearman's rho (r) between TE_{BCC} and the pressure-specific EE were 0.698, 0.590, 0.661, 0.667 and 0.641 for the water use, energy ratio, nitrogen balance, phosphorus balance and pesticide risk, respectively, and were significant at a 0.01 confidence level. From a technical perspective, the farmers did not efficiently manage farm inputs, which enhanced the environmental pressures and negatively affected the environment. Improving the TE can help reduce costs and enhance the EE in cotton farming. From the farmers' social and behavioral perspectives, there are two other important sets of considerations for environmental inefficiency as established by Picazo-Tadeo et al. (2011) and Picazo-Tadeo et al. (2012). First, the farmers generally consider the environmental pressure an externality; second, the farmers do not always consider the direct economic benefit or profit maximization but often consider a complex set of objectives to enhance the utility (e.g., risk minimization, production steadiness, and drudgery avoidance; Ellis, 1998).

5.3 Determinant of efficiency analysis

Table 5.4 shows the bootstrapped left truncated regression results of the environmental efficiency (appendix B–3) at variable return to scale of the selected DMUs. Again, the number of bootstrap replications has been set 2000 following Afonso and St. Aubyn (2006) and Barros and Assaf (2009). The estimated coefficients of the factors that affect different efficiencies of the DMUs are given in the table. In some cases different selected factors affect significantly environmental efficiency of the DMUs such as the farm size, raised-bed sowing, education level and exposure to extension trainings. It was observed that the raised-bed sowing have a statistically significant effect on the environmental efficiency of the DMUs and which suggests that the increased use of mechanical and other management practices cause environmental inefficiencies of the farms. Paradoxically, higher education level relates significantly to environmental inefficiency of the farms, which finding deviates from the usual assumption that higher education can leads to higher efficiency. It is plausible that educated farmers' higher awareness and knowledge of the importance of agrochemicals plays as a negative factor in the sense that they tend to overdose on agrochemical application, which is also made possible by their relatively better-off financial status. In other words, they tend to extensify (use more inputs) instead of intensify production (be more efficient). The other possible reasons of higher education relates significantly to environmental inefficiency because educated farmers consider other objectives. Finally, high exposure to extension services and trainings significantly relates to high environmental efficiency.

Table. 5.4 Truncated bootstrap regression estimates

Variables	Environmental efficiency	
	Coefficients	p-value
Medium farms	- 0.0443	0.012**
Large farms	- 0.00704	0.736
Sowing method	- 0.0255	0.054*
Land tenure	- 0.0011	0.953
High school	- 0.0108	0.562
Beyond High School	- 0.0379	0.014**
Age	0.0002	0.788
Exposure to extension trainings	0.0380	0.013**
Constant	0.8843	0.000***
Sigma	0.0856	0.000***
Wald chi2 (p-value)	28.24	0.0004***

* = Significance level $p \leq 0.10$
** = Significance level $p \leq 0.05$
*** = Significance level $p \leq 0.01$

Chapter 6

Direct Field Emission from Cotton Cultivation in Pakistan: Methods and Emission Factors

6.1 Scope, limitations, and background information

In agricultural systems direct emissions are the pollutants to air, soil and water come from the fields and it is very important to consider these emissions to assess the environmental impacts of agricultural systems. Basically considering direct field emissions is very important at the inventory phase of LCA as it contribute to environmental impacts of the systems. The rest of environmental impacts come from manufacturing of fertilizers, pesticides, machineries and equipment that can be modeled from existing literature and databases. Regarding direct field emissions, it has been chosen to consider emissions of nitrous oxide, nitric oxide, ammonia into air and nitrate and phosphate into surface water or groundwater. Beside emissions from fertilizers, pesticides losses also occur into air, soil or water that contributes toxicities. The emission of carbon dioxide from the field is also a main concern however it is considered neutral as crop absorbs carbon dioxide. Heavy metals and other potential pollutants have been ignored.

The direct emissions to air have been modeled based on the methods developed by International Panel on Climate Change (IPCC, 2006) with some adaptations suggested by regional or site-specific studies. Fertilizers-induced emissions have been calculated based upon cropping calendars. Year-round background emissions have also been considered, on the basis of common cotton cropping calendar. Cotton cropping and related operations usually covers land over six months (from mid-May to mid-November), wheat being the common winter crop. So yearly background emissions were assessed to reflect the specific contribution of cotton cropping systems.

Nitrogen and phosphorus balances can be estimated by calculating the difference between respective elements' inputs (fertilization) and outputs (emissions and plant absorption). If N and P stocks in soil are considered constant, each balance consists of:

N or P Fertilization – N or P Emissions – N or P Plant uptake (exported) = 0 (Equation 1)

Under the same cropping systems (cotton-wheat) for years, soil nitrogen and phosphorus contents through a certain time period show negligible respective differences. As a consequence, N and p soil stocks have been considered constant. Other components such as biological nitrogen fixation (input), and exports by weeds (output) have been ignored. All nitrogen and phosphate applications for fertilization have been recorded in each cropping system.

6.2 N_2O emissions from cotton cultivation to air

Mahmood et al. (2008) studied and tried to quantify N_2O emissions from an irrigated cotton field under semiarid subtropical condition in central region of Punjab province of Pakistan. Cotton is sown in May and is harvested in November. They concluded that high soil moisture and temperature under flooded irrigated cotton are conducive to less N_2O emissions during active crop growth period and they confirmed an emission factor (EF) < 1 % of the applied N fertilizer in the irrigated croplands under similar agro climatic conditions in Pakistan. According to IPCC (2006) the mean value for fertilizer- and manure-induced N_2O emissions is close to 0.9% under irrigated upland conditions;

however, it is considered that, given the uncertainties associated, the round value of 1% is appropriate.

Yan et al. (2003) reviewed literature with measurements of N_2O emissions from some upland crop in Asia. Those included unfertilized plots in order to derive fertilizer-induced emissions. The model is not specific to cotton crop in Pakistan. Also, the paper is oriented towards assessment of total emissions from land use perspective, and considers the emissions throughout the year, including background N_2O emissions. As a conclusion, average fertilizer emission factor was considered 1% of all N fertilizing units applied as suggested by IPCC (2006) and Mahmood et al. (2008), and an average background emission of 1.22 kg N- $N_2O.ha^{-1}$ per year is taken from Yan et al. (2003). Equation 6.1 captures the model that can calculate the N_2O emissions from fertilizers use in cotton cropping systems.

$$N\text{-}N_2O\ kg.ha^{-1} = [EF \times Nf] + [BEF \times D/365] \qquad \text{(Equation 6.1)}$$

where:

Nf: Total N units applied through chemical fertilization, per ha, during cropping cycle

EF: Average fertilizer-induced emission factor (1%)

D: Actual duration of cropping season

BEF: 1.22 N $kg.ha^{-1}$ Average background N-N_2O emission over 365-days

6.3 NOx emissions from cotton cultivation to air

Yan et al. (2003) established through a review of literature based on statistical analysis, that emission factor of NOx is 0.66 % of all N fertilizing units applied for upland crop. Through extrapolation of five measurements they found out that the background NOx emission is approximately 0.58 kg N- $NO.ha^{-1}$ for an entire year. Liu et al. (2010) calculated the emission factor of NOx 0.24% from irrigated cotton field in northern China. Through daily observation of the NOx fluxes, they calculated the annual emission of 0.8 kg N- $NO.ha^{-1}$ for an entire year. In addition they found that soil moisture and temperature can influence the emission of NOx. The agro-climatic condition of Pakistan is semiarid and hot similar to northern China which is semiarid in summer, leading to more emissions therefore it is decided to use the emission factor of NOx 0.0066 from Yan et al. (2003). Equation 6.2 captures that model, which only covers the emission of NOx under average conditions.

$$N\text{-}NO\ kg.ha^{-1} = [\ 0.0066 \times Nf] + [0.58 \times D/365] \qquad \text{(Equation 6.2)}$$

where:

Nf: Total N units applied through chemical fertilization, per ha, during cropping cycle

0.0066: Average fertilizer-induced emission factor (0.66%)

D: Actual duration of cropping season

0.58 N $kg.ha^{-1}$: Average baseline N-NO emission over 365 days

6.4 NH_3 emissions from cotton cultivation to air (volatilization)

Urea is the most common chemical fertilizer that is used in cotton production in Punjab province of Pakistan. Timing and mode of application has a strong influence on volatilization rate. Yan et al. (2003) performed literature analysis on urea-induced NH_3 emissions. They suggested the following: volatilization forms 11.5% of application when incorporation is performed at land preparation, 23.5% when urea is top-dressed (broadcasted). Mostly urea is top-dressed during crop growth period and NH_3 emission factor is therefore considered 23.5%.

$N\text{-}NH_3\ kg.ha^{-1}$ from urea = $(U_{incorp}\times 0.46\times 0.115) + (U_{topdressed}\times 0.46\times 0.235)$ (Equation. 6.3)

where:

0.46:	Conversion factor from N-Urea to Urea
U_{inc} :	Mass of urea applied and incorporated in soil at land preparation time
$U_{topdressed}$:	Mass of urea broadcast (top-dressed) after transplantation / seedling time, during vegetative phase

Due to unavailability of experimental data, Yan et al. (2003), used EEA guidelines, recommended an average NH_3 emission factors 5% from ammonium phosphate. They also recommended a background emission of 1.5 kg $N\text{-}NH_3.ha^{-1}.yr^{-1}$.

Therefore, total NH_3 emissions to air from cotton field may be modeled and calculated as follows:

$$N\text{-}NH_3\ kg.ha^{-1} = [N\text{-}NH_3\ kg.ha^{-1}\ \text{from urea}] + (N\text{-}AP \times 0.05) + (1.5\ kg\ N\text{-}NH_3.ha^{-1}.yr^{-1} \times D/365) \quad \text{(Equation 6.4)}$$

where:

$N\text{-}NH_3\ kg.ha^{-1}$:	N units from urea (see Equation 6.3)
N-AP :	N units from ammonium phosphate ($kg.ha^{-1}$)
D:	Actual cropping cycle duration
$(1.5\ kg\ N\text{-}NH_3.ha^{-1}.yr^{-1} \times D/365)$:	background emission, adjusted to D

6.5 Nitrates emissions from cotton to soil and water

IPCC (2006) provided the emission factor of N loss through leaching and runoff as 30% of the applied nitrogen in the region where soil water holding capacity exceeds due to rainfall and irrigation methods used other than drip irrigation method. In Pakistan cotton crop is irrigated through flood irrigation method therefore 30% of the emission factor is possibly suitable for this study. But actually nitrate emission has been calculated based on nitrogen mass balance.

After calculating the N_2O, NO, NH_3 and N_2 the remaining component of the applied nitrogen is considered as nitrate (NO_3) resulted from nitrification of Ammonia. If nitrate is not absorbed by plant root and taken up as nutrient it will potentially be emitted to water compartment as a pollutant through deep percolation and drainage.

6.5.1 Nitrogen mass balance

The nitrogen balance can be estimated by calculating the difference of nitrogen inputs and nitrogen output and loss.

N fertilization (N_2O + NOx + NH_3 + NO_3 + N_2) – plant absorbed N = 0 (Equation 6.5)

Nitrogen can be applied to the field from different sources and the output can be calculated through measuring the direct nitrogen emissions as well as the amount exported by crop. The nitrogen difference can be calculated by N stored in pre cultivation soil to the N stored in post cultivation soil. Under same cropping systems (cotton-wheat crop rotation) for year the quantity of nitrogen applied during each crop growth period and the quantity of nitrogen taken up by plant remains the same. Similarly Organic matter is also considered balanced overtime as there in same cropping system over time with equal mineralization and immobilization. Therefore both soil organic matter and nitrogen content variations have been ignored in the respective balances. Other component such as biological nitrogen fixation (-) and export by weeds (-) are ignored.

Surface drainage may occur due to over irrigation but for this study it has been ignored and nitrogen loss through surface drainage was considered zero. The amount of nitrate leached down to groundwater compartment has been estimated through water balance.

N input is calculated through fertilizers formula and fertilizers doses.

N input from rainfall, surface irrigation water and groundwater has been calculated through existing studies (averaged data from existing studies).

Nitrogen uptake from cotton plant has been calculated based on the exported mass of plant part that is seed cotton and cotton stalk. Mostly farmers use their cotton stalk as fuel wood and therefore, the average N content of cotton stalk has been calculated based on available data.

N_2O, NO and Ammonia has been calculated as section 6.2, 6.3 and 6.4.

N_2 is also emitted during crop growth period even it is not a pollutant but need to be assessed in order to calculate the nitrogen balance. Emission factor of N-N_2 of 0.09 proposed by (Brentrup, et al., 2000) has been used in this study to calculate the emission of molecular nitrogen.

N-N_2 (kg. ha^{-1}) at the rate of 192 kg nitrogen ha^{-1} = 0.09×192 = 17.28 kg. ha^{-1}

6.5.2 Water Balance

Water balance is necessary in order to determine water use efficiency ratio. Leachable nitrate that leach to the groundwater can also be calculated with the help of water use efficiency that can be expressed by following equation.

Leachable nitrates (NI) = Nt × [1-Ei] (Equation 6.6)

The water balance can be expressed by following equation

$$I + P - ET = R + DWP \qquad \text{(Equation 6.7)}$$

where:

I	= Irrigation water applied in mm
P	= Precipitation in mm
ET	= Evapotranspiration in mm
R	= Runoff from the field or drainage in mm
DWP	= Deep water percolation in mm

In case of cotton crop production systems in Pakistan runoff is considered zero as farmers manage the bunds or the furrows in a way to avoid water from spilling over from the bunds.

Irrigation efficiency is the ratio of the evapotranspiration to precipitation and irrigation water. It is expressed in the following equation.

$$Ei = ET/ (P+I) \qquad \text{(Equation 6.8)}$$

If the factors of deep percolation as well as the runoff are considered then the above equation can be expressed as:

$$1-Ei = (DWP + R)/P + I \qquad \text{(Equation 6.9)}$$

In order to calculate the proportion of nitrate that drained out from the field through deep percolation and running off the water balance is required. ET has been calculated through CROPWAT (FAO, 1992). Average monthly data for rainfall was taken from the Meteorological Department of Pakistan and based on the average monthly rainfall data the amount of rainfall water available to cotton was calculated. The irrigation data of the related system was taken from Irrigation Department of Punjab Province of Pakistan.

6.5.3 Nitrogen input parameters

Generally the given fertilization plan in cotton field in Punjab province of Pakistan is followed:

In early stage at sowing time, 62 kg.ha^{-1} urea (46-0-0)
That is 62 kg.ha^{-1} $\times$ 0.46 = 28.5 kg-N units.ha^{-1}
In the early stage at sowing time, 124 kg.ha^{-1} Diammonium Phosphate (18-23-0)
That is 124 kg.ha^{-1} $\times$ 0.18 = 22 kg-N units.ha^{-1}
During the whole crop growth period excluding the first application of urea fertilizer 309 kg of urea is top dressed that is 309kg.ha^{-1} $\times$ 0.46 = 142 kg-N units.ha^{-1}
Total application rate of N equal to 28.52+22+142 = 192 kg-N ha^{-1}

6.5.4 Nitrogen from precipitation

The average value of nitrate from rainwater is 1.42 mg/ liter in Punjab province of Pakistan (Farooqi et al., 2007). As 1 mm of rainwater is equal to 1 liter of water per square meter of land or in other words it is 10,000 liters per hectare. So, nitrate from 1 mm of rainwater to one hectare can be calculated as follows.

Nitrates per one millimeter of rainwater per hectare = 10,000 liter × 1.42 mg/liter

= 14,200 mg or 0.0142 kilogram nitrates

Rainfall data for last 30 years (1980-2010) of the selected stations was taken from Meteorological Department of Pakistan and is given in the following table.

Table 6.1. Average monthly rainfall data of the selected stations in the study area

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall (mm)	7.0	16.8	10.9	7.1	10.6	26.3	35.9	30.0	14.7	8.5	1.0	8.4

The sowing time of cotton is May and it is harvested by the end of October until mid of November. So the total rainfall from May to October is 126 millimeter and therefore the amount of NO_3 from precipitation available to the field of cotton crop is given as follows.

NO_3 from precipitation = 126 × 0.0142 = 1.7892 kilogram NO_3 per hectare.

To convert nitrate into nitrogen it has been multiplied with 14/62 to get exact amount of nitrogen from rainfall.

The amount of N-NO_3 from rainfall = 1.7892 × 14/62 = 0.4040 kg N-NO_3.ha^{-1}

6.5.5 Nitrogen from canal irrigation water

The average NO_3 concentration of Indus basin irrigation water in Punjab province of Pakistan is 3.28 milligram per liter of the canal water was analyzed by (Karim & Veizer, 2000). It means that 1 millimeter of canal irrigation water brings 0.328 kg of NO_3 per hectare or 0.07411 kg of N per hectare.

6.5.6 Nitrogen from groundwater irrigation

The mean value NO_3 concentration in groundwater water in Punjab province of Pakistan is 1.9 milligram per liter taken from (Farooqi et al., 2007). It means that 1 millimeter of tube well irrigation water brings 0.019 kg of NO_3 per hectare or 0.00429 kg of N per hectare.

6.5.7 Nitrogen output parameters

Different studies have been done to calculate the concentration of nitrogen in different parts of the cotton plant. The average concentration of nitrogen in stem, burs, seed and lint tissues are 0.75%, 0.99%, 3.13% and 0.29% respectively (Pettigrew & Meredith Jr , 1997). Similar nitrogen concentration of nitrogen in harvested cotton stalk, leaves, carpel, delinted cotton seed, lint, roots and plant debris are 0.63%, 2.58%, 1.48%, 3.72%, 0.24%, 1.20% and 1.61% respectively (Boquet & Breitenbeck, 2000; Murphy et al., 2010). After crop harvest leaves and roots remains in the field and contribute to nitrogen immobilization in organic matter. In some cases the farmers use cotton stick as fuel wood and therefore the amount of nitrogen concentration exported through cotton stick must be included in total export. Seed cotton to stick weight ratio was taken as 0.314 (Aujla et al., 2005). Additionally total harvested seed cotton contains average 5-10% of trash in the form of plant debris and carpel that is also removed from the field with seed cotton should be included in nitrogen export (Boquet & Breitenbeck, 2000). In this case the plant debris and carpels export is assumed as 7.5 % the mean values of the proposed by Boquet & Breitenbeck (2000) . The average lint to seed ratio was taken as 0.37 as proposed by (Khan et al., 2010) in Pakistani condition.

Considering a yield of seed cotton an example 1778 kg, total export through seed 37.52, lint 1.42, plant debris 2.86 and cotton stalk 32.10 with total amount 73.89 kilogram on nitrogen export.

6.5.8 Nitrogen Losses through emission to air

The summery of nitrogen losses through emission to air is given as under calculated based on the equations discussed above.

$N\text{-}N_2O$ $kg.ha^{-1}$	= 2.52 (see eq. 6.1)
N-NO $kg.ha^{-1}$	= 1.5532 (see eq. 6.2)
$N\text{-}NH_3$ emissions to air ($kg.ha^{-1}$)	= 14.139 (see eq. 6.4 for detail)
N-N2 emission into air (kg. ha^{-1})	= 0.09 × 192 = 17.28

The excess of the applied nitrogen can be calculated through the difference of input and output.

Table 6.2 Nitrogen balance in cotton crop production

Nitrogen inputs (kg ha^{-1})	Nitrogen outputs (kg ha^{-1})
Fertilizers 192	$N\text{-}N_2O$ (2.52)
Precipitation (0.4040)	N-NO (1.55)
Canal (2.81)	$N\text{-}NH_3$ (14.14)
Groundwater (2.88)	N-N2 (17.28)
	Seed (37.52)
	Lint (1.42)
	Plant debris (2.86)
	Cotton stalk (32.10)
Total input (198)	Total (109.39)
	Nitrate $N\text{-}NO_3$ (total input – total output) 88.61

6.5.9 Nitrate emission and runoff and deep percolation

It is assumed that the remaining part of nitrogen is mostly nitrates after calculating the amount taken up by plants and lost through air emission. These nitrates are taken to the surface and/or ground water compartments through deep percolation or surface drainage. In cotton cropping systems of Pakistan there is no drainage and therefore the amount of nitrate that is drained out through surface runoff was considered zero. Deep water percolation can be calculated as

$DWP + R = P + I - ET$ (Equation 6.10)

In this case the runoff is zero and the average total rainfall during crop growth period is 126 mm. Potential evapotranspiration or reference evapotranspiration can be estimated through Penman-Monteith method as explained in chapter 3.

Actual evapotranspiration (ETa) can be calculated through the ET_0 and K_c which can be calculated through the meteorological data.

$ET_a = ET_o \times K_c$ (Equation 6.11)

The ET_a was determined as 575.01 for the mentioned cotton cropping system in Pakistan.

So DWP can be calculated as DWP + 0 = 839.2 + 126 – 575.01 = 390.19 mm

Water use efficiency can be calculated as

$Ei = 575.01/839.2 \times 100 = 68.52\ \%$

According to the equation 4.10

$1\text{-}Ei = (DWP + R)/ (P + I)$

$= 390/965$

$= 0.404$

So $NI = Nt \times (1\text{-}Ei)$

$= 88.61 \times 0.404$

$= 35.80 \times 62/14$

$= 158.54$ kg $NO_3.ha^{-1}$

Deep percolation is 390 mm meaning that 3,900,000 liter per hectare. It means that the NO_3 concentration in in percolating water is 0.0407 $g.l^{-1}$ or 40.7 $mg.l^{-1}$. This figure lies in the nitrate range (11-160 mg. l^{-1}) in Pakistan reported by Tahir and Rasheed (2008)

6.6 Phosphorus emission from cotton cultivation

Phosphorous is an input used in cotton crop through chemical fertilizer application most commonly through DAP. Rainwater and irrigation water also contain phosphorus that can be added into cotton cropping systems. Phosphorus is exported from cotton cropping systems by taking off the plant part. Losses occur through deep percolation only and runoff is assumed zero as discussed above. The mass balance of phosphorus can be expressed as follows.

$0 = P_{input} - P_{output} - P_{difference\ soil}$ (Equation 6.12)

Soil phosphorus difference is considered negligible because the soil phosphorus content may be assumed constant due to repeated cropping patterns for years. For the same reason organic matter is also considered balanced. Cotton field are surrounded by bunds and there is almost negligible chances of spilling of water over the bunds and the risk of phosphorus through runoff is assumed to be zero.

Phosphorus input from chemical fertilizer is calculated based on the applied fertilizer formula and the doses of applications. Phosphorus input to the cotton cropping system from rainwater and from irrigation water has been calculated based on the concentration of phosphorus in the irrigation water and rainwater.

Phosphorus uptake in cotton plant and export by cotton plant has been calculated based on average mass of the exported plant parts and its phosphorus contents. Mainly seed cotton (seed + lint) is exported from the field and in some cases cotton stick are also exported.

Total phosphorus losses through drainage and leeching to the surface and groundwater can be calculated through water mass balance. It is assumed that the amount of phosphorus that is drain out or leeched down is equal to the proportion of water that is unused by crop during it cycle.

6.6.1 P Input parameters

Generally, P from fertilizers, at sowing time is applied to the field at the rate of 124 $kg.ha^{-1}$ Diammonium Phosphate (18-23-0). That is equal to 124 $kg.ha^{-1} \times 0.23 = 28.52$ kg-P $units.ha^{-1}$

6.6.2 Phosphorus from precipitation

The average value of Phosphate from rainwater has been taken as 0.4 mg/ liter in Punjab province of Pakistan (Farooqi et al., 2007). So, 1 mm of rainwater to one hectare can be calculated as follows.

Phosphate per millimeter of rainwater per hectare = 10,000 liter × 0.4 mg/liter

= 4,000 mg or 0.004 kilogram phosphate

Sowing time of average cotton is May and it is harvested by the end of October until mid of November. So the total rainfall from May to October is 126 millimeter and therefore the amount of PO_4^{3-} from precipitation available to the cotton crop field is given as follows.

PO_4^{3-} from precipitation = $126 \times 0.004 = 0.504$ kilogram PO_4^{3-} per hectare.

The amount of P- PO_4^{3-} from rainfall = $0.504 \times 31/95 = 0.1645$ kg P- $PO_4^{3-}.ha^{-1}$

6.6.3 Phosphorus from canal irrigation

The average P- PO_4^{3-} concentration of Indus basin irrigation water in Punjab province of Pakistan is 0.76 milligram per liter of canal water (Karim & Veizer, 2000). It means that 1 millimeter of canal irrigation water brings 0.0076 kg of P- PO_4^{3-} per hectare or 0.00248 kg of P per hectare.

6.6.4 Phosphorus from groundwater irrigation

The Phosphorus concentration in groundwater water in Punjab province of Pakistan is considered negligible as analyzed by (Farooqi et al., 2007).

Total P input $= P_{fertilizer} + P_{canal\ irrigation} + P_{precipitation} + P_{grounwater}$ (Equation 6.13)

6.6.5 Phosphorus output parameters

The average concentration of Phosphorus in stem, burs, seed and lint tissues are 0.11%, 0.20%, 0.60% and 0.40% respectively (Pettigrew & Meredith Jr, 1997). Leaves and roots remain in the field after picking of cotton crop and it contribute to phosphorus immobilization. In some cases the farmers use cotton stick as fuel wood and therefor the amount of phosphorus concentration exported through cotton stick must be included in total export. Seed cotton to stick weigh ratio was taken as 0.314 (Aujla et al., 2005). Additionally total harvested seed cotton contains on average 5-10% of trash in the form of plant debris and carpel that is also removed from the field with seed cotton that should be included in Phosphorus export (Boquet & Breitenbeck, 2000). The amount of the additional phosphorus can be exported through plant debris together with seed cotton. Additional weight of plant debris has is assumed as 7.5 % of the weight of seed cotton with phosphorus concentration of 0.30 % (Rochester, 2007). The average lint to seed ratio was taken as 0.37 as proposed by (Khan et al., 2010) in Pakistani condition.

It is assumed that the remaining phosphorus is phosphate salts and will potentially be emitted to groundwater and surface water compartments as pollutant through percolation and drainage. The ratio of (ET/DWP + D) can help to assess the phosphate losses as pollutant. It is assumed that the phosphate concentration is same in ET, DWP and D.

6.6.6 Losses through drainage and deep percolation

As the cotton fields are protected by bunds and it is assumed that there is no spilling over of water and ultimately there is no run off phosphate losses.

P losses through deep percolation can be calculated by

$PI = Pt \times [1-Ei]$

Where Pt is 14.2 P/ ha (that is the amount of excess phosphorus units potentially leachable to ground or surface water.

And $[1-Ei] = 0.404$

Therefore

$PI = 14.2 \times 0.404 = 5.737$ kg P units/ha

Or $5.737 \times 95/31 = 17.58$ PO_4 /ha of phosphate.

6.7 Pesticides emissions from cotton cultivation

Different types and quantity of pesticides are applied in cotton cropping systems depending on the insect pest outbreak. Applied pesticides are partially deposited on leaf surface and partially on soil surface. Emission of pesticides occurs through volatilization either from plant leaf surface, soil surface or through spray drift. Pesticides emissions to air have been calculated by applying EEA (2009) method through multiplying mass of active ingredient with corresponding emission factors. The emission factor depends on the vapor pressure of the given product. After calculating the quantity volatilized with emission factor, the remaining part has been considered as the emission to soil and groundwater.

6.8 Conclusions

The methods presented here will be mobilized to carry out the life cycle analysis as discussed in the following section.

Chapter 7

LCA-Based Environmental Performances and Eco-Efficiency Analyzes

This chapter includes eco-efficiency analysis of cotton cropping systems based on the environmental impacts indicators analyzed through Life Cycle Assessment (LCA) approach by using primary data from the study area as well as data from secondary sources. Environmental impact indicators have been used to compute eco-efficiency of each cropping system that was documented. The eco-efficiency of cotton farming was assessed with the help of the Data Envelopment analysis (DEA). Mean values of eco-efficiency has been compared among different farm categories. Based on the applied quantity of physical inputs by each farm and their respective monetary cost as well as the gross income of the produce, the value addition or net income has been calculated, which was ultimately used to compute eco-efficiencies of different cropping systems.

7.1 Life Cycle Inventory (LCI) analyzes

7.1.1 Field Operation

Field operations data required for cotton cultivation includes soil preparation (deep ploughing, rotary tillage, leveling and seedbed preparation), fertilizing, pesticide application, water management, sowing, weeding and picking. Each operation has been documented for each studied DMU in terms of machinery used, amount used and area of application. All these operations generate environmental impacts through fuel burning and resources used. All data of field operations was related to a functional unit of 1 kilogram of seed cotton produced as shown in Table 7.1, and also to one hectare used for production as shown in table 7.5. Statistical analysis through Kruskal-Wallis test, a non-parametric approach and an alternate to Analysis of Variance (ANOVA), shows that field operations among farm size groups are significantly different except tillage operations, sowing and electricity and large farms were using more inputs and small were using least inputs to produce 1 kilogram of seed cotton as shown in table 7.1. A statistically significant difference among farm groups was also found in field operations as per hectare of cotton crop for all variables where medium farms utilizes higher inputs except tillage operations and electricity use as shown in table 7.5.

7.1.2 Pesticides application

A variable amount and type of pesticides are used in cotton production depending upon the occurrence of pest. The average doses of different commercial pesticides used by different farms were collected through field survey and were modeled according to the active ingredients. The doses of different groups of pesticides as per functional unit were compared among different farm size groups and it was observed that the doses of Parathyroid and Phenoxy compounds are statistically significantly different among different farm groups as shown in table 7.2. Significant differences were also observed in per hectare doses of Organophosphate, Pyrethroids and Phenoxy compounds among different farm groups as shown in table 7.6.

7.1.3 Fertilizers' application

Different amount of fertilizers are used by different farms depending upon field characteristics. Average amount of fertilizers data used by each farm has been collected through field survey and modeled. The nitrogen (N), Phosphorus (P_2O_5) and Potassium (K_2O) or NPK percentage (%) of Urea (46, 0, 0), Diammonium Phosphate (18, 46, 0), Single Super Phosphate (0, 14, 0), Triple super phosphate (0, 46, 0), Ammonium Nitrate (26, 0, 0) and Potassium Sulphate (0, 0, 50) have been modeled accordingly to produce one kilogram of seed cotton based on the amount applied per hectare of cotton crop. Zinc sulphate ($ZnSO_4$) was also modeled as per functional unit based on the dose applied per hectare. Statistically significant differences among different farm groups were found in the use of Phosphorus fertilizers and Zinc sulphate as per functional unit as shown in table 7.3. Statistical significant difference of nitrogen, phosphorus and Zinc sulphate application per hectare were also observed among different farm groups as shown in table 7.7.

7.1.4. Direct field emissions

Field emissions of cotton crop have been modeled based on the methods discussed in chapter 6. The environmentally damaging field emissions of cotton crop into air are; nitrous oxide, nitrogen oxide, and ammonia and into water are nitrate and phosphate. Beside these direct field emissions, a certain amount of pesticides emit into air and into soil and water compartment and has been modeled accordingly. It was found that the difference in the emissions of nitrous oxide, nitrogen oxide and phosphate are statistically significant among different farm groups as shown in table 7.4. However no statistical significant differences were observed in the emission on per hectare cotton crop among different farm groups as shown in table 7.8.

The modeled field emissions of cotton cropping systems are slightly higher compared to the field emissions of the existing experimental results (972.3±868.0 g N ha-1) (Tariq et.al., 2008). The difference was observed because of the higher doses of nitrogen fertilizers (approximately 190 kg ha^{-1}, however 100 kg ha^{-1} nitrogen has been used by Tariq et.al, (2008) in their experimental study. Similar figures have also been reported by Liu et. al, (2010)

It was observed that Imidacloprid was the most common pesticide used by farmers and because of its cheaper price; small farmers with less resources were using this product intensively. The environmental impact through the cultural management practices by small farms was observed lower as they are more labor intensive. Similarly manual pesticide spray was common in small farms, which is more effective and is responsible for less environmental impacts. But on the other side due to economies of scale small farms were taking more time for tillage operations compared to medium and large.

Canal irrigation water is equally distributed among different farms based on per unit area. But small farmers tend to use more irrigation water and use fossil energy to pump groundwater and in this way they are more responsible for higher environmental impact through irrigation process. Beside that small farmers were using less sulphuric acid to de-lint the seed but medium and large farms were using more because they need to de-lint seed in bulk.

Table 7.1 Descriptive statistics of production factors use (per 1000 kg of seed cotton)

		Small		Medium		Large		
Inventory	Units	**Mean**	SD	**Mean**	SD	**Mean**	SD	p-value
Land use[a]	ha	**0.4988**	0.298	**0.4592**	0.230	**0.5009**	0.241	0.04**
Water use	m^3	**5947**	2386	**4823**	1783	**5019**	1515	0.02**
Ploughing	ha.hour	**5.50**	3.15	**4.48**	2.78	**4.31**	2.26	0.16
Rotary tillage	ha.hour	**1.36**	1.12	**1.52**	1.26	**0.81**	1.07	0.00***
Field leveling	ha.hour	**0.88**	0.42	**1.17**	0.89	**0.84**	0.65	0.07*
Sowing	ha.hour	**1.01**	0.78	**1.07**	0.61	**1.00**	0.61	0.74
Cultural management/weeding	ha hour	**1.13**	1.21	**1.64**	2.20	**3.08**	2.51	0.00***
Mechanical pesticides spray	ha.hour	**1.94**	4.01	**5.73**	6.16	**10.04**	5.33	0.00***
Electricity	kWh	**568.3**	319.4	**487.7**	212.1	**503.0**	187.9	0.29
Sulphuric Acid	liter	**0.92**	0.82	**1.39**	0.77	**1.66**	0.69	0.00***

* = Significance level $p \leq 0.10$; ** = Significance level $p \leq 0.05$; *** = Significance level $p \leq 0.01$

[a] Land use refers to direct cotton production only, i.e. cotton plots; seed production areas, and required built areas have been ignored

Table 7.2 Descriptive statistics of the pesticides used (as per 1000 kg of seed cotton)

		Small		Medium		Large		
Inventory	Units	**Mean**	SD	**Mean**	SD	**Mean**	SD	p-value
Pesticides (unspec.)	kg a.i[a]	**1.80**	1.27	**0.97**	0.76	**1.30**	1.15	0.30
Organophosphates	kg a.i	**0.84**	0.56	**1.06**	0.83	**0.83**	0.64	0.32
Pyrethroids	kg a.i	**0.12**	0.13	**0.18**	0.19	**0.26**	0.26	0.01^{**}
Phenoxy compounds	kg a.i	**0.70**	0.77	**1.17**	1.28	**1.58**	1.03	0.00^{***}
Weedicides	kg a.i	**0.84**	0.64	**1.06**	0.96	**1.09**	1.05	0.75

[a] active ingredient; * = Significance level $p \leq 0.10$; ** = Significance level $p \leq 0.05$; *** = Significance level $p \leq 0.01$

Table 7.3 Descriptive statistics of the fertilizers used (as per 1000 kg of seed cotton)

		Small		Medium		Large		
Inventory	Units	**Mean**	SD	**Mean**	SD	**Mean**	SD	p-value
Nitrogen-based	kg	**153.24**	57.56	**153.90**	68.45	**163.61**	62.84	0.41
Phosphates	kg	**31.05**	21.68	**38.61**	24.38	**40.42**	22.72	0.01^{**}
Potassium	kg	**0.04**	0.15	**0.31**	1.76	**0.54**	2.29	0.58
Zinc sulphate	kg	**1.35**	3.11	**2.80**	5.81	**4.59**	5.90	0.00^{***}

* = Significance level $p \leq 0.10$; ** = Significance level $p \leq 0.05$; *** = Significance level $p \leq 0.01$

Table 7.4 Descriptive statistics of direct nitrogen and phosphorus emissions (as per 1000 kg of seed cotton produced)

		Small		Medium		Large		
Inventory	Units	**Mean**	SD	**Mean**	SD	**Mean**	SD	p-value
N_2O emission	kg	**1.99**	0.71	**1.74**	0.58	**1.94**	0.61	0.06^{*}
NO emission	kg	**1.23**	0.44	**1.08**	0.37	**1.21**	0.38	0.08^{*}
NH_3 emission	kg	**20.00**	7.63	**17.92**	6.63	**19.62**	6.59	0.17
NO_3 emission	kg	**222.96**	114.83	**206.62**	105.64	**202.22**	85.81	0.61
PO_4 emission	kg	**30.12**	27.51	**18.20**	12.80	**19.21**	13.56	0.04^{**}

* = Significance level $p \leq 0.10$; ** = Significance level $p \leq 0.05$; *** = Significance level $p \leq 0.01$

Table 7.5 Descriptive statistics of production factors use (per hectare of land used in cotton production systems)

Variables	Units	**Small farms** Mean	Small farms SD	**Medium farms** Mean	Medium farms SD	**Large farms** Mean	Large farms SD	p-value
Water Use	m^3	**9270.0**	2510.0	**9310.0**	1890.0	***8670.0***	1970.0	0.05**
Rotary tillage	ha-hours	**1.92**	1.13	**3.06**	2.69	***1.52***	2.24	0.00***
Seedbed leveling	ha-hours	**1.40**	0.87	**2.22**	1.63	**1.61**	1.80	0.00***
Sowing	ha-hours	**1.54**	0.83	**2.12**	1.15	**1.76**	1.18	0.00***
Cultural management practices/weeding	ha-hours	**2.42**	3.12	**3.22**	4.01	**5.39**	4.61	0.00***
Pesticides spray	ha-hours	**5.13**	9.31	**11.80**	13.00	**17.10**	9.74	0.00***
Sulphuric Acid	liter	**1.52**	1.08	**2.65**	1.39	**2.77**	1.16	0.00***

* = Significance level $p \leq 0.10$; ** = Significance level $p \leq 0.05$; *** = Significance level $p \leq 0.01$

Table 7.6 Descriptive statistics of the pesticides used (as per hectare of land used in cotton systems)

		Small farms		Medium farms		Large farms		
Variables	Units	**Mean**	SD	**Mean**	SD	**Mean**	SD	p-value
Organophosphates	kg a.i[a]	**1.460**	1.020	**2.110**	1.520	**1.550**	1.270	0.03**
Pyrethroids	kg a.i[a]	**0.235**	0.249	**0.351**	0.365	**0.429**	0.487	0.07*
Phenoxy compound	kg a.i[a]	**1.360**	1.440	**2.230**	2.210	**2.840**	2.180	0.00***

a = active ingredient; * = Significance level $p \leq 0.10$; ** = Significance level $p \leq 0.05$; *** = Significance level $p \leq 0.01$

Table 7.7 Descriptive statistics of fertilizers used (as per hectare of cotton crop in cotton systems)

		Small farms		Medium farms		Large farms		
Inventory	units	**Mean**	SD	**Mean**	SD	**Mean**	SD	p-value
Nitrogen fertilizers	kg	**254.00**	111.00	**312.00**	161.00	**295.00**	145.00	0.02**
Phosphorus fertilizers	kg	**53.80**	39.20	**79.90**	53.80	**72.00**	49.80	0.01**
Zinc Sulphate	kg	**3.03**	6.22	**6.51**	14.20	**8.64**	10.20	0.00***

* = Significance level $p \leq 0.10$; ** = Significance level $p \leq 0.05$; *** = Significance level $p \leq 0.01$

Table 7.8 Descriptive statistics of direct nitrogen and phosphorus emissions (as per hectare of cotton crop in cotton systems)

		Small farms		**Medium farms**		**Large farms**		
Inventory	Units	**Mean**	SD	**Mean**	SD	**Mean**	SD	p-value
N_2O emission	Kg	**3.25**	1.17	**3.46**	1.26	**3.41**	1.06	0.16
NO emission	Kg	**2.02**	0.76	**2.17**	0.83	**2.13**	0.69	0.14
NH_3 emission	Kg	***33.10***	14.30	**36.00**	15.20	**34.70**	12.50	0.10*
NO_3 emission	Kg	**366.00**	219.00	**411.00**	273.00	**367.00**	195.00	0.16
PO_4 emissions	Kg	**50.10**	52.60	**38.10**	38.10	**38.70**	47.20	0.44

* = Significance level $p \leq 0.10$; ** = Significance level $p \leq 0.05$; *** = Significance level $p \leq 0.01$

The results of N_2O estimated in this study (Table 7.8) were compared with the results obtained by Tariq et al. (2008) from their experiments conducted in Punjab, Pakistan. It has been confirmed that that the results of N_2O emission estimated in this study (2.25-3.46 kg/ha) are within the range of the results of N_2O emission obtained by Tariq et al. (2008) (0.972 ± 0.868 kg/ha). In their experiments they have used only 100 kg nitrogen/ ha but at field level farmers use higher quantity of nitrogen fertilizers ranging 254-312 kg/ha. Similarly comparing water crop water requirement (Table 7.5) calculated in the study (867-927 m^3/ha) are also within the range of reported cotton crop water requirement 763-915 m^3/ha (Cherrett et al., 2005) and 550-950 m^3/ha (Koositra et al., (2005).

7.2 Computing environmental impacts variables from life cycle assessment

In this stage LCI information has been translated into impact indicators, using SimaPro 7.2.3 software and Ecoinvent database. The CML 2 baseline characterization method developed by the Center for Environmental Studies (Guinée, 2001) has been selected, leading to several mid-point indicators as shown in table 7.9. One additional variable (irrigation water use) was selected as a notably important environmental indicator for water-scarce arid Pakistan. The method and indicators were selected based upon their popularity in LCA studies on agriculture (Abeliotis et al., 2013, Cellura et al., 2012, Khoshnevisan et al., 2014, Romero-Gámez et al., 2012 and Thanawong et al., 2014), and easiness to comprehend by non-specialists in Pakistan. Table 7.9 shows the environmental impact indicators that have been used.

Table 7.9 Selected environmental impact categories

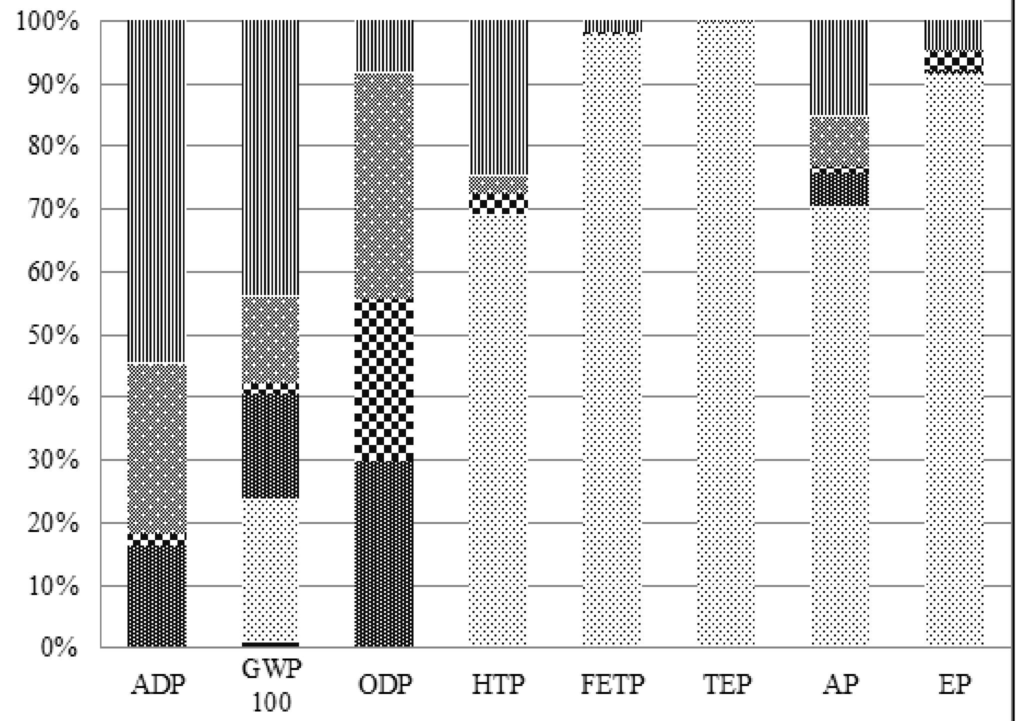
Environmental impact categories	Units
Abiotic depletion potential (ADP)	kg Sb eq
Global warming potential (GWP_{100})	kg CO_2 eq
Acidification potential (AP)	kg SO_2 eq
Eutrophication potential (EP)	kg PO_4^{3-} eq
Human toxicity potential (HTP)	kg 1,4-DB eq
Fresh water aquatic ecotoxicity potential (FETP)	kg 1,4-DB eq
Terrestrial ecotoxicity potential (TETP)	kg 1,4-DB eq
Ozone layer depletion (ODP)	kg CFC-11 eq
Water use (WU)	m^3 H_2O

7.2.1 Contribution analysis

Figure 7.1 represents the contribution of different inputs and field operations to the environmental impacts. Direct field emissions contribute to most toxicity-related, acidification and eutrophication impacts, due to high pesticide and fertilizer use. Irrigation is the major contributor of abiotic resources depletion, global warming potential and photochemical oxidation potential, due to water use, energy use (through groundwater pumping and fossil fuel consumption).

Fertilizer manufacturing and transportation are contributing much to energy and fossil-fuel use (reflected by ADP and GWP) and to photochemical oxidation potential. They also, with pesticide manufacturing and transport contribute to ozone depletion. Field operations are mainly motorized, so they contribute much to energy use and fossil-fuel combustion (reflected by ADP and GWP). They also contribute significantly to ozone depletion.

Overall, the most important sources of environmental impacts in cotton cropping systems of Southern Punjab are irrigation (through groundwater pumping), fertilizer and pesticide uses, and motorized field operations. Direct field emissions seem particularly harmful (toxicity), due to excessive use of fertilizer and pesticides, leading to high emissions to air and water compartments.



	ADP	GWP 100	ODP	HTP	FETP	TEP	AP	EP
Irrigation	54,50	43,91	8,30	24,62	2,01	0,01	15,16	4,64
Fertilizers	27,17	13,84	35,85	2,91	0,00	0,02	7,87	0,19
Pesticides	1,89	1,34	25,99	3,24	0,05	0,00	0,88	2,66
Field operations	16,44	17,22	29,86	0,00	0,04	0,00	5,53	1,15
Field emissions	0,00	22,87	0,08	69,21	98,14	99,90	70,42	91,23
Seed production	0,20	0,82	0,00	0,16	0,06	0,08	0,12	0,14

Figure 7.1 Contribution of cotton cropping inputs and operations to environmental impacts.

7.3 Environmental impacts variability based on mass of seed cotton

The environmental impact categories with corresponding mean values per kilogram of seed cotton are shown in table 7.10. Energy use is included in the Abiotic (resources) Depletion Potential indicator (ADP). Mean values of potential environmental impacts expressed per one kilogram of seed cotton of each farm category were compared. Eutrophication potential is significantly higher in small farms (due to higher phosphate and nitrate emissions per FU, and lower yields). Similarly water use is also significantly higher in small farms due to higher irrigation water use and lower yield. Small farms are also showing higher ADP, AP, and GWP though not significantly different. All remaining environmental impacts, related to toxicity potentials, are higher in medium sized farms.

According to our results, production of 1 kg of seed cotton delivered at farm gate generates a global warming potential of 3 to 3.4 $kgCO_{2e}$ and requires 5 to 6 liters of water, of which 75 to 80% is irrigation water. Overall, farm size does not play an important role in the level of impacts. Differences remain limited between farm classes, and mostly due to differences in yields.

Table 7.10. Average environmental impacts from the different farm size classes, per kilogram of seed cotton

Variables	Units	Farm size	Mean	SD	P-values
ADP	kg Sb eq	Small	0.0220	0.0098	0.404
		Medium	0.0200	0.0096	
		Large	0.0197	0.0070	
		Overall	0.0204	0.0088	
AP	kg SO_2 eq	Small	0.0544	0.0210	0.255
		Medium	0.0486	0.0166	
		Large	0.0507	0.0170	
		Overall	0.0507	0.0176	
EP	kg PO_4^{3-} eq	Small	0.0666	0.0360	0.016*
		Medium	0.0522	0.0240	
		Large	0.0533	0.0213	
		Overall	0.0560	0.0270	
GWP_{100}	kg CO_2 eq	Small	3.4184	1.5014	0.329
		Medium	3.0588	1.3583	
		Large	3.0842	1.0306	
		Overall	3.1531	1.2886	
HTP	kg 1,4-DB eq	Small	2.8708	1.4345	0.461
		Medium	2.8887	1.6584	
		Large	2.6003	1.0556	
		Overall	2.7804	1.4110	
FETP	kg 1,4-DB eq	Small	4.6341	8.9380	0.063*
		Medium	6.9506	7.2189	
		Large	4.3058	4.1697	
		Overall	5.4477	6.8617	
TETP	kg 1,4-DB eq	Small	1.1956	4.0622	0.219
		Medium	1.3380	2.5829	
		Large	0.5223	1.6632	
		Overall	1.0099	2.7600	
WU	m^3 H_2O	Small	5.9468	2.3863	0.02**
		Medium	4.8228	1.7827	
		Large	5.0187	1.5154	
		Overall	5.1595	1.9118	

* = Significance level $p \leq 0.10$; ** = Significance level $p \leq 0.05$

7.4 Eco-efficiency analysis

Statistics presented in table 10 for the environmental impact variables used in the eco-efficiency analysis of cotton farming systems in Punjab, Pakistan. The input-oriented eco-efficiency of each DMU has been computed using data envelopment analysis (DEA), calculating the potential reduction of each environmental impact while maintaining the net income. The eco-efficiency has been computed by using added value of one kilogram of seed cotton (un-ginned cotton). Seed cotton yield varies from DMU to DMU, therefore to understand the yield effect the eco-efficiency has also been computed with the added value per hectare of cotton crop of each DMU. Yield of seed cotton varies as the input used by each DMU varies depending upon the cultural and management practices the farmer follows which ultimately produces diverse environmental impact. The comparison of the eco-efficiency with the added value of one kilogram of seed cotton and the added value of one hectare of cotton crop by each DMU give a clear picture to understand.

Table 7.12 summarises the results of the eco-efficiency analysis using DEA. The analysis showed that the overall mean eco-efficiency computed with the net income per hectare of cultivated cotton is higher compared to the eco-efficiency computed with the net income per kilogram of seed cotton produced. The eco-efficiency scores for all of the farm categories were estimated by using all of the growers as a reference to calculate the eco-efficiency, assuming a variable return to scale (VRS). Only 11 DMUs (i.e. only 6.51%) were found fully efficient when the eco-efficiency was performed based on the functional unit of one kilogram of cotton produce which indicate that other farmer are producing given level of income with more environmental impacts. Similarly when eco-efficiency analysis was performed with the net income per hectare then it was found that 26 DMUs (i.e. only 15.38%) were fully efficient. The Kruskal-Wallis test was applied to the indices for efficiency (i.e., per kilogram cotton- and per hectare eco-efficiencies) to determine whether the efficiencies of different farms categories were significantly different. A statistical significant difference in the eco-efficiency among different farm categories has also been observed when eco-efficiency was computed with the net income of cotton produced per hectare. Eco-efficiency of the small farms was the highest, which means that the small farms made better use of the inputs and resources than medium and large farms as DEA shows that higher economic return offset the negative impacts of small farms. Computing eco-efficiency with the value addition per kilogram of seed cotton, showed no significant difference among different farm categories. Statistically significant differences between the eco-efficiencies per hectare all of farm sizes using a VRS indicated that these farmers are using different levels of inputs in per unit area. Eco-efficiency based on the physical amount of produce does not depend on the size of the farm but it depends on other factors.

Table 7.11 Eco-efficiency scores (averages as per farm size and overall)

	Small		Medium		Large		Overall		P values
	Mean	SD	**Mean**	SD	**Mean**	SD	**Mean**	SD	
EE (mass)	**0.514**	0.203	**0.515**	0.246	**0.492**	0.205	**0.507**	0.222	0.897
EE (area)	**0.857**	0.146	**0.735**	0.159	**0.783**	0.167	**0.781**	0.166	0.001*

Eco-efficiency (mass) = Eco-efficiency based on the net income per kilogram of cotton
Eco-efficiency (area) = Eco-efficiency based on the net income per hectare of cotton crop
* = Significance level $p \leq 0.05$

Table 7.12 Observed and projected quantities of potential environmental impacts

		Small		Medium		Large	
Variables		Mean	SD	Mean	SD	Mean	SD
Abiotic resources depletion	Observed	**0.02**	0.01	**0.02**	0.01	**0.02**	0.01
	Projection	**0.01**	0.00	**0.01**	0.00	**0.01**	0.00
	%age reduction	**56.23**	20.75	**54.29**	24.08	**56.44**	18.99
Acidification Potential	Observed	**0.05**	0.02	**0.05**	0.02	**0.05**	0.02
	Projection	**0.02**	0.00	**0.02**	0.00	**0.02**	0.00
	%age reduction	**54.95**	19.43	**53.77**	22.43	**56.06**	18.18
Eutrophication Potential	Observed	**0.07**	0.04	**0.05**	0.02	**0.05**	0.02
	Projection	**0.02**	0.01	**0.02**	0.01	**0.02**	0.01
	%age reduction	**56.28**	21.96	**55.63**	26.68	**56.13**	22.75
Global Warming Potential (GWP_{100})	Observed	**3.42**	1.50	**3.06**	1.36	**3.08**	1.03
	Projection	**1.23**	0.33	**1.14**	0.29	**1.20**	0.20
	%age reduction	**56.98**	20.47	**54.94**	22.84	**56.16**	18.18
Human toxicity	Observed	**2.87**	1.43	**2.89**	1.66	**2.60**	1.06
	Projection	**0.83**	0.18	**0.79**	0.20	**0.78**	0.12
	%age reduction	**63.78**	21.59	**62.24**	25.95	**63.51**	18.77
Fresh water aquatic eco-toxicity	Observed	**4.63**	8.94	**6.95**	7.22	**4.31**	4.17
	Projection	**0.50**	0.36	**0.72**	0.55	**0.62**	0.25
	%age reduction	**69.07**	25.87	**72.99**	27.05	**72.53**	21.31
Terrestrial eco-toxicity	Observed	**1.20**	4.06	**1.34**	2.58	**0.52**	1.66
	Projection	**0.02**	0.01	**0.03**	0.02	**0.02**	0.01
	%age reduction	**66.83**	28.07	**71.31**	29.44	**72.09**	24.81
Water use	Observed	**2.97**	1.31	**2.95**	1.30	**2.87**	0.94
	Projection	**1.20**	0.43	**1.15**	0.21	**1.15**	0.16
	%age reduction	**53.08**	21.33	**53.04**	22.37	**55.11**	18.77

Table 7.13 indicates the potential reduction in environmental impacts to reach at 100% efficiency level for each farm category. Eco-inefficiency can be explained by technical inefficiency. From a technical perspective, the farmers do not manage farm inputs efficiently, and this inefficient management enhances environmental impacts and negatively affected the environment. This analysis just put together environmental impact and net income. It tries to identify which DMU have lower impact and higher income and to quantify the potential for reduction of impacts for the least efficient one. Low eco-efficiency is always a result of low income or higher impacts. Improving technical efficiency can help enhancing eco-efficiency in cotton farming.

Figure 7.2 represent the percentage potential reduction of environmental impacts computed through eco-efficiency analysis with added value of one kilogram of seed cotton as output and figure 7.3 represents the %age potential reduction of environmental impacts computed through eco-efficiency analysis with added value of yield per hectare and its corresponding potential environmental impacts. These potential reductions show the margin for progress to achieve eco-efficiency.

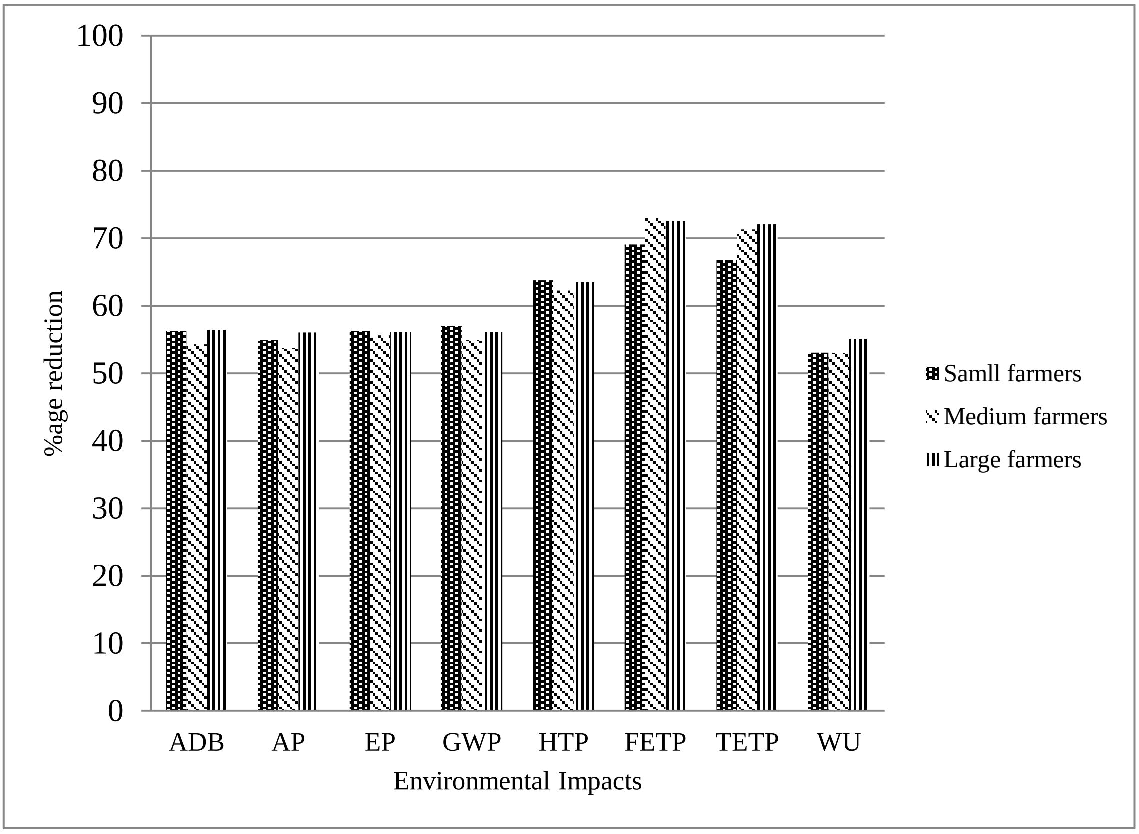


Figure 7.2 Percentage potential reductions of environmental impacts/kg seed cotton

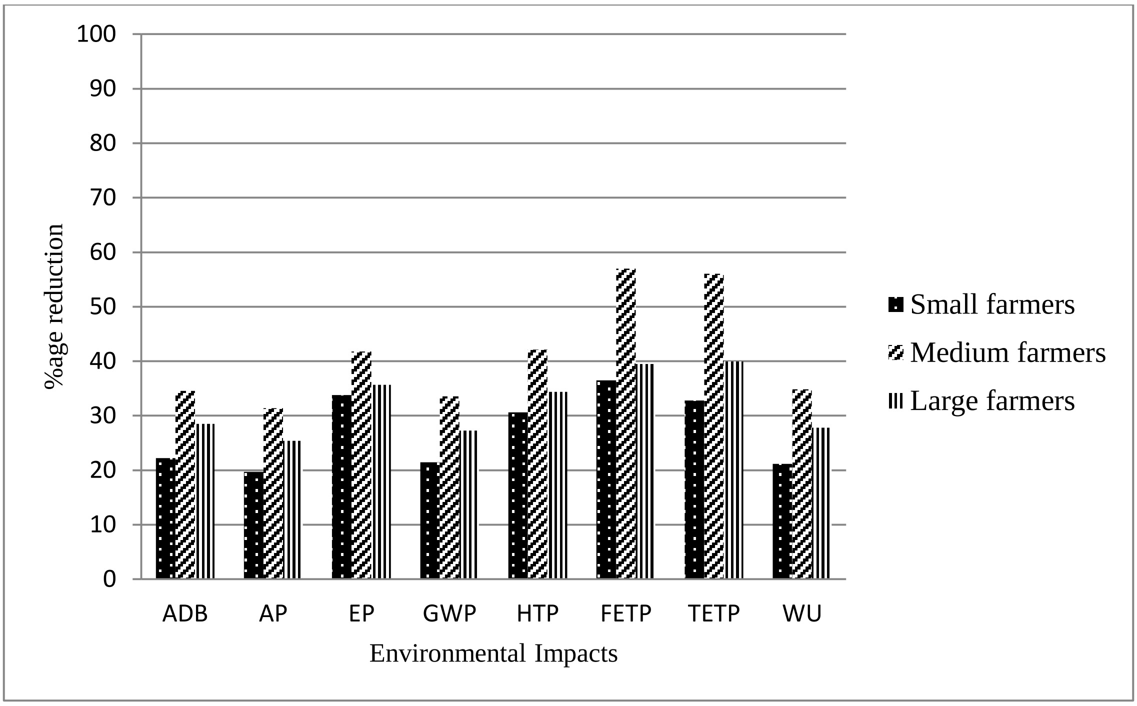


Figure 7.3 Percentage potential reductions of environmental impacts/kg seed cotton

7.5 Determinant of eco-efficiency

Table 7.14 shows the bootstrapped left truncated regression results of the eco-efficiency as per kilogram of seed cotton produce (appendix B–4) and eco-efficiency per hectare of cotton crop (appendix B–5) at variable return to scale of the selected DMUs. The number of bootstrap replications has been set to 2000. The estimated coefficients of the factors that affect different efficiencies of the DMUs are given in the table. In some cases different selected factors affect significantly on eco-efficiency per hectare of the DMUs such as the farm size, raised-bed sowing and education level. Farmers prefer to grow cotton on the raised- seedbed in order to avoid damages occurs due to rainfall if it happens in early stages of crop growth and to save irrigation water which ultimately needs extra management activities. It was observed that the raised-bed sowing have a statistically significant effect on the eco-efficiency of the DMUs and which suggests that the increased use of mechanical and other management practices cause eco-inefficiencies of the DMUs. Paradoxically, higher education level relates significantly negatively to eco-efficiency of the farms both in terms of per kilogram seed cotton produce and in terms of per hectare of cotton crop , which finding deviates from the usual assumption that higher education can leads to higher efficiency. It is plausible that educated farmers' higher awareness and knowledge of the importance of agrochemicals plays as a negative factor in the sense that they tend to overdose on agrochemical application, which is also made possible by their relatively better-off financial status. In other words, they tend to extensify (use more inputs) instead of intensify production (be more efficient).

Table 7.13 Truncated bootstrap regression estimates

Explanatory variables	Explained variable			
	Eco-efficiency as per kilogram of seed cotton		Eco-efficiency as per hectare of seed cotton produce	
	Coeff.	p-value	Coeff.	Significant differences
Medium farms	-0.0268	*	-0.1172	***
Large farms	-0.0826	n.s	-0.0479	n.s
Sowing method	-0.0656	*	-0.0060	*
Land tenure	0.0873	n.s	0.0440	n.s
High school	-0.0507	n.s	0.0757	**
Beyond High School	-0.1827	**	-0.0092	n.s
Age	0.0010	n.s	-0.0006	n.s
Exposure to extension trainings	-0.0025	n.s	0.0232	n.s
Constant	0.6914	***	0.8242	***
Sigma	0.2210	***	0.1534	***
Wald chi2 (p-value)	19.09	**	40.10	***

n.s. = not significant
* = Significance level $p \leq 0.10$
**= Significance level $p \leq 0.05$
***= Significance level $p \leq 0.01$

7.6 Sustainability and trade-off analysis

7.6.1 Comparing performances at the cropping system level

A percentile analysis of performance indicators was performed to investigate sustainability, as the combination of high technical, economic and environmental performances. Among the sampled cropping systems (169 DMUs), the 10% with highest eco-efficiency, the 10% with highest net income, the 10% with lower environmental impacts (several indicators), and the 10% with lower production costs were identified as sub-groups (deciles), then compared with each other. Results are reported in table 7.15. All deciles include 17 out of 169 DMUs, consisting of small, medium and large sized farms. There is no overlapping (systems are completely different altogether) between the “high income” decile and the “low production costs”, and “low environmental impact” deciles respectively, except for 2 DMUs that are common to both “high income” and “low eutrophication” deciles. However it was observed that “highest eco-efficiency” decile are partially overlapping with highest net income and partially with low production cost and low environmental impacts. Only single DMUs has been found similar to one having low production cost. All other DMUs with highest eco-efficiency score are overlapping with highest net income or lower environmental impacts.

Results clearly show that the 10% DMUs with higher net income are not those DMUs with low environmental impacts. Within the decile with higher net income, 41% only were eco-efficient, 52% are technically efficient and 58% are cost efficient. A closer look to the given DMUs show that the best systems with respect to higher net income are those who are growing their crop earlier and on raised seedbed (ridge cropping). These systems were getting higher yield compared to others and thus higher net income. Ridge cropping (raised seedbeds) requires extra management care and ultimately higher fossil fuel use. These systems are responsible for higher environmental impacts due to extra use of fossil energy for management activities as well as increased amount of agro-chemicals due to extended life span of cotton crop.

Further analysis showed that none of the 10% systems with low production cost are eco-efficient. Within this decile 11 DMUs are common with 2 to 5 DMUs of the low environmental impact deciles. So, in practice, “low production costs” rather refer to “low environmental impacts” than to “higher income” in cotton systems of Punjab.

It was observed that 13 of the 17 DMUS of the “low production cost” decile were technically efficient and those 13 were also all cost efficient. Majority of these DMUs (10) were practicing flat seedbed cropping through drill-sowing where less management activities were required. These DMUs were using much less water per hectare compared to those better systems with higher net income. The benefits of consuming less water are twofold: water saving and energy saving (lower electricity consumption for water pumping). Due to low yield and ultimately low net income these DMUs were eco-inefficient.

The descriptive percentile analysis also showed that farm size has no striking impact on the different performances, with the notable exception of “low GWP decile” which is mostly populated (13 over 17) with DMUs from large farm size group.

Table 7.14 List of 10% DMUs' numbers (among 169 cropping systems) with higher net income, lower production cost and lower environmental impacts

10% higher EE	10% highest net income	10% lowest total cost	10% lowest GWP	10% lowest AP	10 % lowest EP	10% lowest HTP	10% lowest TETP	10% lowest FETP	10% lowest WU
3	3	1	16	1	3	9	1	1	1
16	13	6	36	5	8	15	9	9	2
17	16	21	102	19	17	39	15	15	8
44	17	24	104	26	25	40	18	19	10
50	37	25	115	30	26	57	26	25	12
56	38	39	128	67	30	79	39	39	39
69	44	40	129	85	61	89	40	40	53
79	50	53	130	102	93	93	56	56	56
90	69	61	131	115	99	99	79	79	65
93	90	85	132	128	102	121	85	85	99
95	94	128	140	130	115	128	89	89	128
104	95	140	150	131	128	130	109	93	130
112	111	153	154	140	130	142	118	109	131
113	112	154	160	142	131	160	121	121	159
128	113	161	165	150	154	162	142	142	160
157	157	162	168	154	159	168	158	163	168
158	164	169	169	165	169	169	160	160	169

Small farms
Medium farms
Large farms

7.6.2 Comparing efficiencies at cropping system level

Comparing and analyzing the technical- and eco-efficiency of the entire DMUs, it was observed that most of the technical efficient systems were eco-inefficient as shown in figure 7.3. The eco-efficiency score of majority i.e. 63% of DMUs were less the 0.50 but among those many of those DMUs were operation technically at an efficient level with their technical efficiency score equal to 1. It was observed that only 9 DMUs have their technical- and eco-efficiency score equal to 1. This trend can be explained by allocative efficiency as described in chapter 4 and it was found that out of 169 DMUs only 5 DMUs having their technical-, allocative- cost- and eco-efficiency score equal to ‘1’. Other DMUs with technical- and allocative efficiency score ‘1’ have eco-efficiency score less than ‘1’ or vice versa which shows that these DMUs gives the competing results where cost and environmental improvement is at the expense of the other criterion (Lauwers, 2009). It shows that there is trade-offs between the technical efficient and eco-efficient DMUs and yet it is another proof that full sustainability is very difficult to achieve with current production practices and technology.

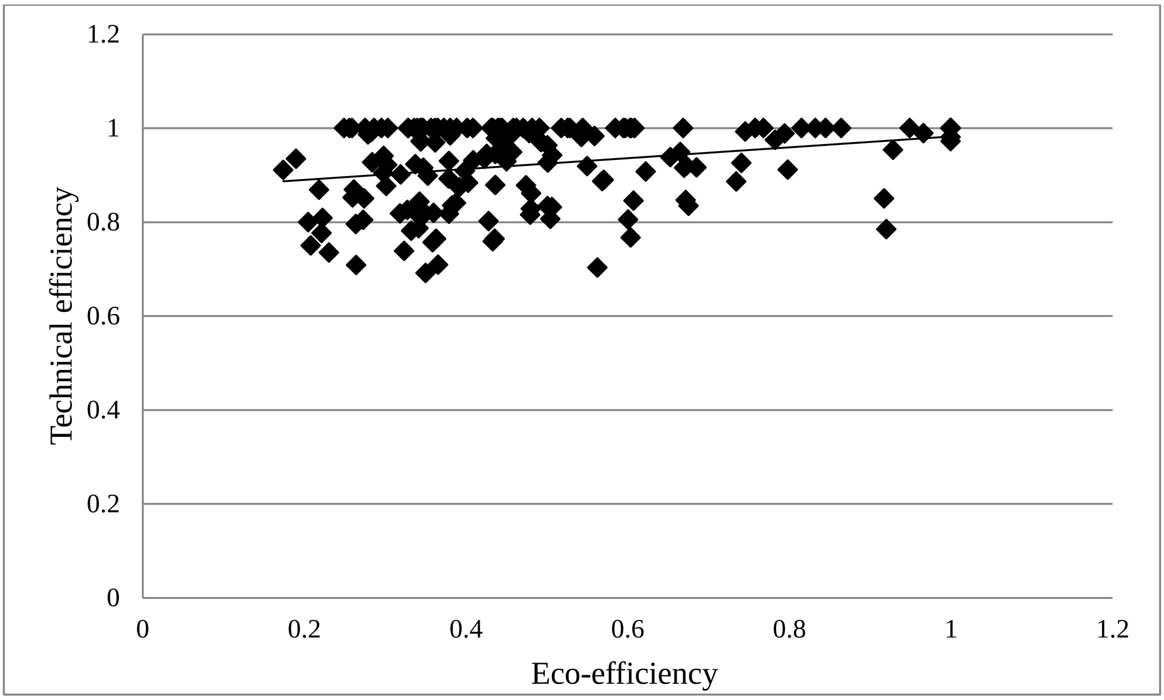


Figure 7.4 Link between the technical-and eco-efficiency scores under VRS assumption of 169 cotton farms

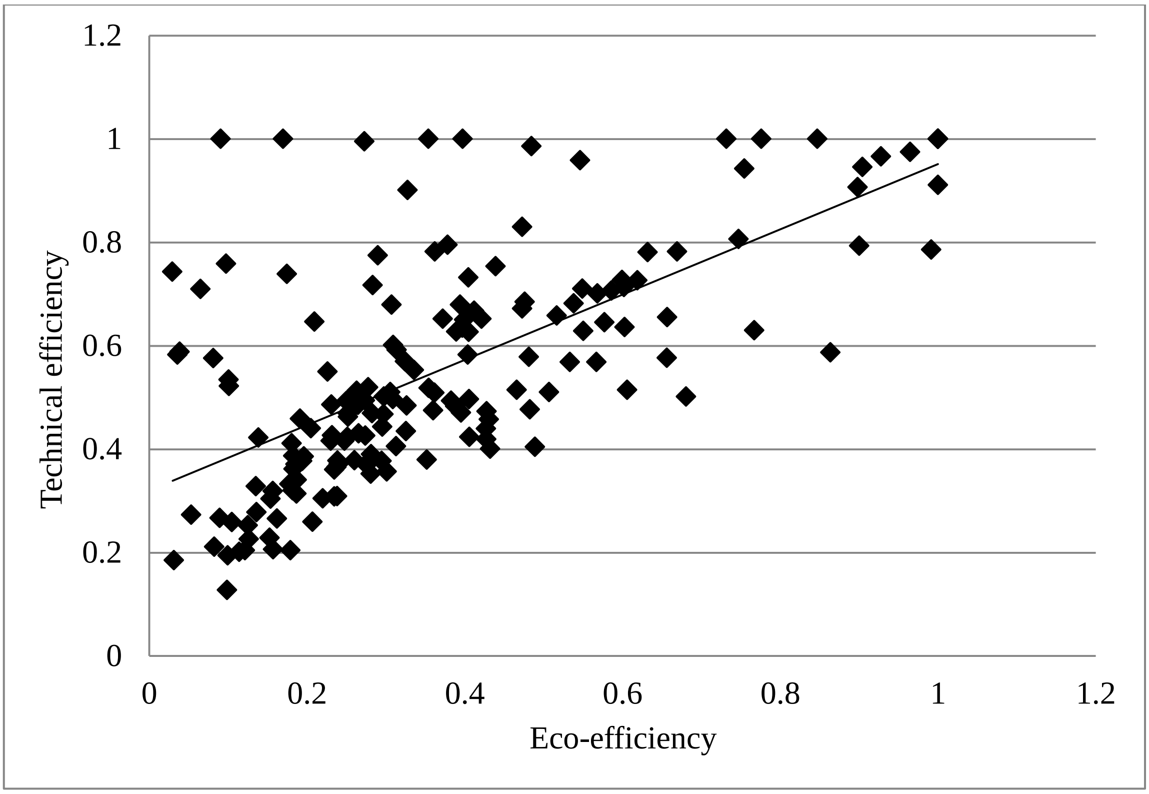


Figure 7.5 Link between the technical-and eco-efficiency scores under CRS assumption of 169 cotton farms

A further detailed analysis of the technical- and eco-efficiency scores under CRS assumption was performed. Through this analysis it was observed that the eco-efficiency score of 129 DMUs i.e. 76% of the entire selected DMUs were less than 0.50 as shown in figure 7.4 but among those 4 DMUs were operating technically at an efficient level with TE score equal to 1. It shows that majority of the DMUs are eco-inefficient. Only 5 DMUs having their technical- and eco-efficiency score equal to 1, were considered the best performing DMUs also with allocative- and cost efficiency score equal to 1. Among all DMUs 5 DMUs were having their eco-efficiency score eco-efficiency score less than 1 but above 0.90. The remaining DMUs i.e. 28 DMUs or 17 % of DMUs were operating at the range of eco-efficiency score 0.50 to 0.90. On the other hand TE of 47% of all the selected DMUs under CRS assumption was less than 0.50. 12 DMUs were operating technically at an efficient level with TE score 1, 10 DMUs operating between less than 1 but above 0.90. This analysis also confirmed that the technical efficiency and eco-efficiency scores sometime gives the competing results which confirms that trade-offs exist between cost and environment.

Further analysis has also been performed between TE and potential environmental impact improvement as shown in figure 7.5. From figure 7.5, it is clear that the DMUs with lower TE are those that have higher potential of environmental impacts improvement. In this case improvement in TE may lead to better environmental performance. But it was also observed that DMUs with higher TE having higher potential of environmental impacts improvement which helped to conclude that the higher TE or even TE score equal 1 was achieved at the cost of environment. It confirmed that trade-offs exist between cost and environment but most specifically in those DMUs where higher cost and TE exist but low eco-efficiency.

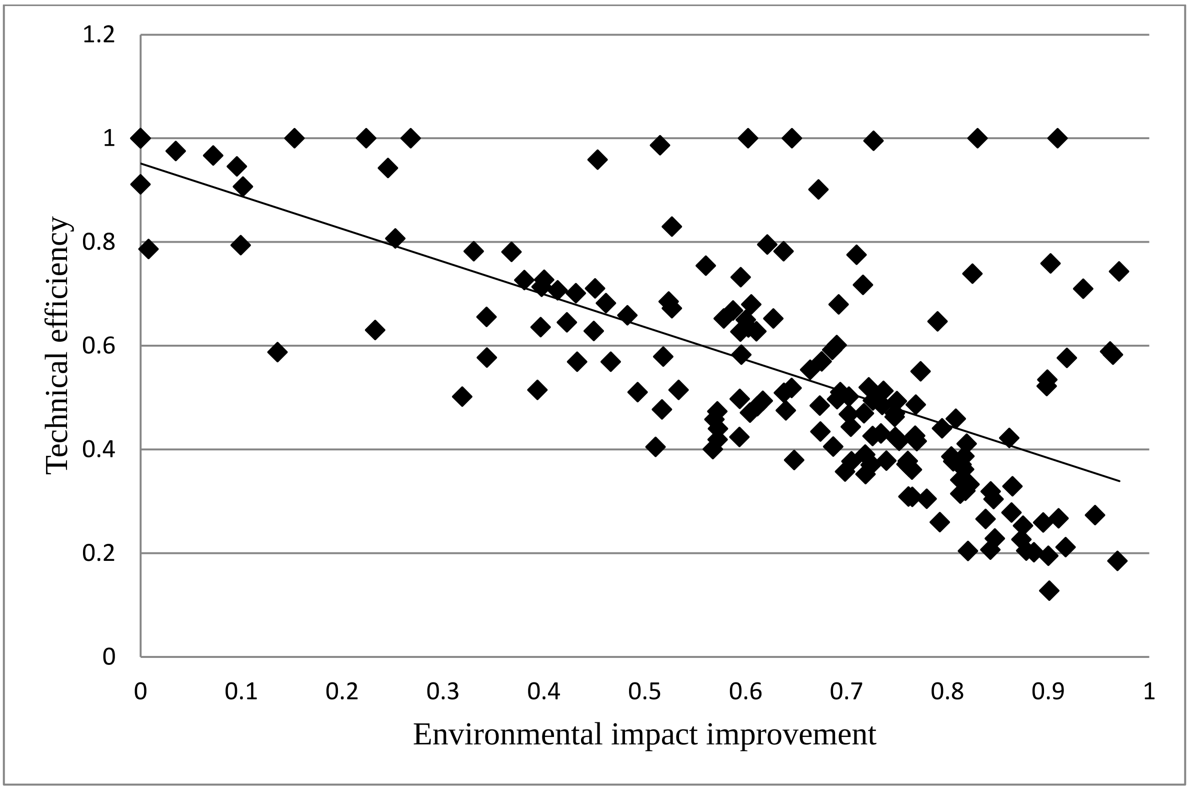


Figure 7.6 Link between environmental impact improvement potential and technical efficiency

Chapter 8

Conclusions and Recommendations

8.1 Justification, approach and design of the research: a summary

Cotton cropping systems are important contributors to the economy of Pakistan, bringing rural income, employment, and export revenues. Yet, they also use massive amounts of water and energy resources and agrochemical inputs (especially pesticides), which results in detrimental impacts onto society (health) and the natural environment. Moreover, at times when consumers are increasingly environmentally aware, and demand information on the quality and safety of the agricultural products they use, it is necessary to assess adequately the production conditions and impacts of commodities such as cotton fibre. Overall, it is a question of sustainability that is posed by cotton production systems, including, at least, technical, economic and environmental dimensions.

This research is based upon the premises that the sustainability of cotton cropping systems in Pakistan may be improved, and that sources of improvement may be found in studying and documenting the patterns and diversity of existing systems, with a multi-criteria approach.

The objectives of the research were first to identify and describe a wide diversity of cotton cropping systems, second to document and analyze jointly their techno-economic and environmental performances, third to jointly analyze their technical, economic and environmental efficiencies, and fourth to discuss their sustainability, and potential improvement pathways, in view of the performance and efficiency indicators.

This study was of empirical nature and analyzed jointly the techno economic and environmental performances of 169 irrigated cotton cropping systems in Punjab, as the chief cotton production area of Pakistan. Specific attention was put on farm size as a possible factor influencing performances and efficiencies. Farms were therefore classified as small, medium and large farms, according to national standards.

The technical and economic performances of each farm size group were assessed based on the inputs and resources used, yields achieved, and the production costs incurred. The analysis of productivities of different inputs was also performed. Environmental performances of each DMU were analyzed through both farm-level ad-hoc environmental indicators and LCA based indicators. Relatively simple, ad-hoc environmental indicators were computed in order to provide a more accessible assessment of environmental performances of cotton production systems, for clear understanding of stakeholders, and methodological convenience. LCA based approach and indicators are more complex and numerous, although more accurately describing impacts. The research aimed also to perform that comparison of methodologies. Technical-, cost- and environmental efficiencies of the sampled farms were determined using data envelopment analysis (DEA). Measuring the efficiencies of cropping systems (as Decision-Making Units, DMUs) with DEA also allows to identify and quantify the potential reductions of inputs and environmental impacts in inefficient DMUs while maintaining the level of economic return, for them to attain full efficiency.

8.2 The research's most salient findings

Overall, the wide diversity of practices, performances and impacts among cotton cropping systems was confirmed, although they pertain to a relatively homogenous production area (Southern Punjab, Pakistan).

The production costs of small farmers are significantly lower than those incurred by medium and large farmers with regards to labor, fuel and pesticide uses. Fossil energy, pesticides and labor productivities of small farms are higher compared to medium farms. Pesticides productivity of small farms is also significantly higher compared to large farms. Net income of medium farms is highest compared to small and large farms and the latter two groups have almost similar net income. But the benefit-cost ratio of small farms is significantly higher compared to medium farms.

The average technical efficiency of small farmers is the highest with an efficiency score of 0.958, followed by medium (0.917) and large farms (0.911). These technical efficiency scores are a bit higher than those reported by Javed, (2009) in cotton-wheat cropping systems in Pakistan (0.87). All farm categories are relatively inefficient overall, but the scale efficiency of medium farmers is higher compared to small farmers. All of the inefficient farmers are operating with increasing return to scale, which means that they are producing inefficiently small level of output. In other words, yields remain sub-optimally low compared to overall production efforts. The results also indicate that there is a substantial opportunity to manage the inputs properly to get a better economic return with less environmental impact and less cost. Results of this study shows that farm size and education beyond high school have negative influence on the efficiency of cotton cropping systems. Extension trainings have a positive and significant effect on the technical efficiency.

Overall, cropping systems are highly eco-inefficient. The main contributors to environmental impacts are pesticides, fertilizers and fossil fuel which contribute mostly to global warming, eutrophication and toxicities through emissions to air and soil. LCA and farm-level ad-hoc indicators show the same trend. The eco-efficiency of small farms is the highest followed by large and medium farms.

On product mass basis, large farms use more inputs such as weeding and pesticide sprays, phosphate and sulphate treatments. The medium and large size farms are using higher quantity of phenoxy and pyrethroids compound respectively compared to small farms. However, emissions of N_2O and NO to air and PO_4 to water are higher in small farms. Overall, the main environmental impacts in cotton production systems are caused be the field emissions of pesticides and fertilizers followed by energy use.

The higher eco-efficiency of small farms indicates that small farms make better use of the inputs and resources than medium and large farms and that higher economic return offset the negative impacts of small farms.

Sustainability analysis based upon compared performance indicators and efficiency scores indicates that trade-off seems inescapable in cotton cropping systems. From empirical data, it appears hardly possible to achieve jointly high economic performance with low environmental impacts. Further, the most profitable systems are not the ones that minimize production costs, while some convergence is observed at system level between lower production cost and lower environmental impacts. Under current technology, farmers' objectives and practices, there is little room to improve together all aspects of sustainability.

8.3 Contribution and originality of this research

The research performed and related in the present document is original, from different perspectives:

First, this research is the first of its kind done in Pakistan, addressing jointly techno-economic and environmental performances of cotton cropping systems. Both the methodology used, and the results gained may be of use to scholars, researchers, managers and policy-makers in Pakistan. Second, the research was multi-disciplinary in nature, combining classic (yet not so common) techno-economic analysis with ambitious Life Cycle Assessment of a large number of cropping systems. Proper understanding of agronomic, technical, economic, and environmental engineering concepts and tools was required. Third, the research relied mostly on primary data, which were collected in a large number of cropping units (169); such approach diverge from the typical techno-economic approaches based upon regional statistics in developing countries. Fourth, LCA application cases in agricultural production, although on the rise, remain rare, especially in developing countries. Further, the combination of LCA with DEA is new and hardly applied in developing contexts. Fifth, efficiencies, and particularly eco-efficiency, have been used to approach, quantify, and discuss the sustainability of the systems under study. Such approach is original.

The contribution of this research spans over several aspects. First, important results are highlighted, in terms of the relative technical, economic and environmental inefficiency of the systems. Also, small size farms seem to perform better than their larger counterparts, in many aspects. Pesticide and fertilizer uses have been identified as the main sources of environmental impacts and inefficiencies. Also, the research revealed that increasing sustainability of cotton cropping systems under current farmers' practices and objectives, and technology, is hardly achievable with no trade-off. It seems that high economic return to production is not compatible with low production costs and low environmental impacts at the moment. Building upon current systems and farmers' experience may not suffice. More engaging policy measures and incentives to push trade-offs to happen may be needed. In particular, limitations on pesticide use should be considered. Also, since most cropping systems still operate under increasing return to scale, there seem to remain certain limiting factors to production which do not allow the full expression of other inputs such as agrochemicals. Further research on irrigation scheduling and nitrogen fertilization, among others, may be needed to investigate.

In terms of methodology, the combination of LCA with DEA proves extremely fruitful. Also, an alternative approach to environmental impact assessment has been used, with farm-level ad-hoc indicators. Such approach proved interesting and may be more accessible and faster to implement than LCA, although yielding more limited, less accurate outcomes. In any case, its results are showing the same trends and issues than the ones of LCA.

Eco-efficiency analysis based on value added per individual environmental impact is a common approach but to produce a single value of eco-efficiency through aggregating the environmental impacts is a challenging task. The contribution of this research is also that it produced a single value of eco-efficiency (using either ad-hoc environmental impact and

LCA indicators) for each system, as a proxy to its sustainability. Such score also compensate for the lack of one single environmental impact score per system.

Temporal variations always exist regarding input use and yield due to different climatic conditions. In this study only one year data has been used to assess techno-economic and environmental performances and efficiency analysis. To address this issue several year data is recommended future studies to make the results generalized.

The findings of this study can help formulate some policy intervention to improve the economic and environmental performances of cotton farms. Considering the environmental-specific efficiency, improved environmental performance and higher cost efficiency can be achieved if the farmers are more technically efficient. Therefore, extensive training regarding the amount, timing and application methods for agro-chemicals could help increase cost efficiency and eco-efficiency. Eco-efficiency can also be improved through learning programs, such as farmer-to-farmer communication, demonstrations, experiments and capacity building, for farmers of various efficiencies. The cost and environmental impacts can be avoided by using the required amount of fertiliser. Some other policy interventions, such taxes on pesticides and fertilisers or banning more lethal products, could be helpful in reducing the impact on the environment.

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Appendix A: Correlation matrix of efficiency (2-tailed Spearman's correlation coefficient)

	[a] TE_{CCR}	[b] TE_{BCC}	[c] CE	[d] AE	[e] SE	[f] EE_{BCC}	[g] EEwater	[h] EE_{Energy}	[i] $EE_{Nitrogen}$	[j] $EE_{Phosphorus}$	[k] $EE_{Pesticides}$
[a] TE_{CCR}	1										
[b] TE_{BCC}	.371**	1									
[c] CE	.457**	.629**	1								
[d] AE	.373**	.250**	.905**	1							
[e] SE	.973**	.161*	.350**	.355**	1						
[f] EE_{BCC}	.278**	.504**	.440**	.277**	.183*	1					
[g] EE_{WATER}	.247**	.494**	.419**	.259**	.154*	.986**	1				
[h] EE_{Energy}	.340**	.317**	.313**	.227**	.280**	.610**	.622**	1			
[i] $EE_{Nitrogen}$	.139	.508**	.537**	.392**	.029	.758**	.746**	.591**	1		
[j] $EE_{Phosphorus}$	.278**	.341**	.453**	.382**	.212**	.492**	.467**	.537**	.609**	1	
[k] $EE_{Pesticides}$	.226**	.406**	.407**	.274**	.144	.631**	.605**	.278**	.569**	.434**	1

** Correlation is significant at 0.01 level (2-tailed)

* Correlation is significant at 0.05 level (2-tailed)

[a] Total technical efficiency

[b] Pure technical efficiency

[c] Cost efficiency

[d] Allocative efficiency

[e] Scale efficiency

[f] Environmental efficiency variable return to scale

[g] Water use pressure specific environmental efficiency

[h] Energy ration pressure specific environmental efficiency

[i] Nitrogen balance pressure specific environmental efficiency

[j] Phosphorus balance pressure specific environmental efficiency

[k] Pesticides risk pressure specific environmental efficiency

Appendix B. Supplementary Tables

Appendix B–1: Technical efficiency scores and bias corrected estimates of efficiency through bootstrapping approach

Farm sizes	DMU	Technical efficiency	Bias	Mean	Median	Std. Dev.	CI Lower Bound	CI Upper Bound
Small farms	1	1.0000	0.0899	0.9101	0.9037	0.0616	0.7917	0.9943
	2	0.9691	0.0284	0.9406	0.9418	0.0128	0.9092	0.9626
	3	1.0000	0.1083	0.8917	0.9075	0.0798	0.7684	0.9941
	4	1.0000	0.0738	0.9262	0.9162	0.0423	0.8545	0.9936
	5	1.0000	0.0839	0.9161	0.9008	0.0482	0.8354	0.9922
	6	0.9979	0.0504	0.9475	0.9600	0.0371	0.8703	0.9920
	7	0.9879	0.0387	0.9491	0.9531	0.0225	0.8939	0.9815
	8	1.0000	0.0444	0.9556	0.9616	0.0283	0.8893	0.9934
	9	0.9427	0.0304	0.9123	0.9145	0.0158	0.8782	0.9367
	10	1.0000	0.0791	0.9209	0.9168	0.0520	0.8169	0.9941
	11	0.9161	0.0473	0.8688	0.8749	0.0320	0.7821	0.9107
	12	0.9921	0.0278	0.9643	0.9653	0.0130	0.9373	0.9856
	13	0.7493	0.0478	0.7015	0.7128	0.0371	0.6114	0.7450
	14	0.9291	0.0330	0.8961	0.8975	0.0174	0.8598	0.9235
	15	1.0000	0.1079	0.8921	0.9122	0.0839	0.7482	0.9947
	16	0.7994	0.0421	0.7573	0.7585	0.0262	0.7030	0.7955
	17	0.6826	0.0351	0.6475	0.6539	0.0271	0.5719	0.6786
	18	0.9325	0.0358	0.8967	0.8980	0.0184	0.8558	0.9261
	19	1.0000	0.0575	0.9425	0.9444	0.0354	0.8657	0.9945
	20	1.0000	0.0819	0.9181	0.9134	0.0565	0.8011	0.9943
	21	1.0000	0.0721	0.9279	0.9332	0.0502	0.8240	0.9947
	22	0.8407	0.0448	0.7959	0.7985	0.0271	0.7455	0.8359
	23	0.9288	0.0194	0.9094	0.9101	0.0075	0.8925	0.9234
	24	0.9657	0.0408	0.9249	0.9314	0.0271	0.8553	0.9590
	25	1.0000	0.0635	0.9365	0.9340	0.0367	0.8671	0.9941
	26	1.0000	0.0910	0.9090	0.9053	0.0625	0.7969	0.9945
	27	1.0000	0.0824	0.9176	0.9073	0.0502	0.8274	0.9935
	28	0.8788	0.0249	0.8539	0.8555	0.0122	0.8271	0.8737
	29	0.8691	0.0503	0.8188	0.8234	0.0322	0.7477	0.8637
	30	1.0000	0.1451	0.8549	0.8990	0.1342	0.5283	0.9946
	31	0.9447	0.0258	0.9188	0.9200	0.0125	0.8909	0.9389
	32	1.0000	0.1002	0.8998	0.9099	0.0809	0.7086	0.9942
	33	0.9344	0.0333	0.9010	0.9024	0.0177	0.8604	0.9293
	34	1.0000	0.1228	0.8772	0.8977	0.0933	0.7193	0.9927
	35	0.7823	0.0364	0.7459	0.7514	0.0228	0.6956	0.7776
	36	1.0000	0.1090	0.8910	0.9036	0.0812	0.7558	0.9938
	37	0.6737	0.0337	0.6400	0.6414	0.0193	0.6006	0.6694
	38	0.6377	0.0253	0.6124	0.6142	0.0147	0.5787	0.6342
	39	0.9720	0.0369	0.9351	0.9374	0.0211	0.8851	0.9662
	40	0.9926	0.0580	0.9346	0.9427	0.0405	0.8351	0.9866
Medium farms	41	0.9098	0.0331	0.8768	0.8786	0.0185	0.8376	0.9042
	42	0.8607	0.0307	0.8300	0.8314	0.0168	0.7960	0.8563
	43	0.9822	0.0483	0.9340	0.9423	0.0305	0.8725	0.9764
	44	0.7674	0.0391	0.7283	0.7380	0.0303	0.6462	0.7627
	45	1.0000	0.1232	0.8768	0.9058	0.0992	0.6924	0.9934

46	0.8182	0.0339	0.7843	0.7865	0.0184	0.7467	0.8139
47	0.8085	0.0252	0.7833	0.7850	0.0137	0.7523	0.8032
48	0.8603	0.0272	0.8330	0.8324	0.0122	0.8108	0.8560
49	0.8438	0.0366	0.8072	0.8082	0.0199	0.7675	0.8387
50	1.0000	0.1332	0.8668	0.8940	0.1072	0.6682	0.9931
51	0.7996	0.0273	0.7722	0.7743	0.0147	0.7378	0.7951
52	0.8484	0.0183	0.8301	0.8310	0.0082	0.8124	0.8436
53	0.9697	0.0469	0.9227	0.9341	0.0410	0.8135	0.9645
54	0.9156	0.0356	0.8800	0.8801	0.0184	0.8440	0.9105
55	0.8938	0.0457	0.8482	0.8499	0.0273	0.7887	0.8887
56	0.8687	0.0270	0.8417	0.8416	0.0109	0.8201	0.8636
57	0.8829	0.0333	0.8496	0.8498	0.0160	0.8167	0.8773
58	0.7849	0.0356	0.7493	0.7572	0.0268	0.6827	0.7805
59	1.0000	0.1405	0.8595	0.9049	0.1312	0.5399	0.9942
60	0.9293	0.0405	0.8887	0.8932	0.0242	0.8354	0.9243
61	1.0000	0.1024	0.8976	0.9079	0.0772	0.7506	0.9943
62	1.0000	0.0913	0.9087	0.8989	0.0606	0.8022	0.9935
63	0.9948	0.0453	0.9495	0.9576	0.0311	0.8762	0.9885
64	0.9155	0.0319	0.8836	0.8851	0.0168	0.8470	0.9098
65	0.9833	0.0307	0.9525	0.9560	0.0168	0.9157	0.9775
66	0.8523	0.0263	0.8261	0.8261	0.0112	0.8026	0.8470
67	0.9098	0.0305	0.8792	0.8834	0.0174	0.8374	0.9045
68	0.8498	0.0249	0.8249	0.8262	0.0118	0.7986	0.8446
69	0.6586	0.0288	0.6298	0.6294	0.0149	0.6003	0.6549
70	0.9808	0.0427	0.9381	0.9468	0.0290	0.8767	0.9758
71	1.0000	0.0641	0.9359	0.9371	0.0406	0.8557	0.9941
72	0.8778	0.0324	0.8454	0.8446	0.0153	0.8178	0.8730
73	0.8100	0.0209	0.7891	0.7909	0.0104	0.7658	0.8054
74	0.8847	0.0468	0.8379	0.8416	0.0292	0.7753	0.8796
75	0.8382	0.0341	0.8041	0.8059	0.0179	0.7697	0.8337
76	0.8194	0.0193	0.8001	0.8012	0.0095	0.7789	0.8147
77	0.9263	0.0343	0.8920	0.8941	0.0177	0.8571	0.9215
78	1.0000	0.1162	0.8838	0.9102	0.0946	0.7033	0.9944
79	0.9618	0.0380	0.9238	0.9263	0.0209	0.8844	0.9550
80	0.7764	0.0283	0.7480	0.7501	0.0153	0.7156	0.7722
81	0.8912	0.0263	0.8649	0.8642	0.0113	0.8432	0.8858
82	0.8134	0.0200	0.7934	0.7934	0.0078	0.7770	0.8090
83	0.8013	0.0234	0.7779	0.7779	0.0111	0.7555	0.7959
84	0.8891	0.0193	0.8699	0.8708	0.0087	0.8498	0.8840
85	1.0000	0.1408	0.8592	0.9072	0.1370	0.5415	0.9944
86	0.8734	0.0207	0.8527	0.8529	0.0084	0.8355	0.8687
87	0.7957	0.0248	0.7709	0.7734	0.0144	0.7353	0.7910
88	0.8170	0.0326	0.7843	0.7857	0.0173	0.7469	0.8115
89	1.0000	0.1085	0.8915	0.9062	0.0808	0.7426	0.9924
90	0.9047	0.0301	0.8745	0.8737	0.0130	0.8497	0.8998
91	1.0000	0.0538	0.9462	0.9499	0.0321	0.8806	0.9949
92	0.8814	0.0332	0.8482	0.8480	0.0173	0.8140	0.8758
93	0.9616	0.0327	0.9288	0.9322	0.0180	0.8861	0.9568
94	0.8333	0.0260	0.8073	0.8127	0.0196	0.7587	0.8294
95	0.7077	0.0408	0.6669	0.6721	0.0268	0.6115	0.7032
96	0.7643	0.0266	0.7377	0.7400	0.0159	0.7026	0.7599
97	0.9344	0.0223	0.9121	0.9128	0.0091	0.8929	0.9287
98	0.9277	0.0394	0.8884	0.8899	0.0218	0.8434	0.9225
99	0.9880	0.0333	0.9547	0.9561	0.0184	0.9187	0.9824

	100	0.9094	0.0305	0.8788	0.8793	0.0136	0.8508	0.9035
	101	0.9120	0.0301	0.8819	0.8810	0.0137	0.8556	0.9065
	102	1.0000	0.0657	0.9343	0.9642	0.0690	0.7569	0.9956
	103	0.7566	0.0285	0.7282	0.7298	0.0148	0.6982	0.7525
	104	0.8706	0.0327	0.8379	0.8367	0.0150	0.8103	0.8651
	105	0.7629	0.0277	0.7351	0.7347	0.0139	0.7095	0.7586
	106	0.7258	0.0175	0.7083	0.7086	0.0077	0.6918	0.7218
	107	0.7382	0.0189	0.7193	0.7198	0.0092	0.6994	0.7337
	108	0.8848	0.0347	0.8501	0.8508	0.0181	0.8113	0.8800
Large farms	109	0.9487	0.0230	0.9258	0.9261	0.0094	0.9061	0.9430
	110	0.8313	0.0220	0.8093	0.8106	0.0105	0.7837	0.8260
	111	0.7952	0.0386	0.7567	0.7594	0.0230	0.7067	0.7905
	112	0.7656	0.0403	0.7252	0.7314	0.0280	0.6596	0.7617
	113	0.7804	0.0565	0.7240	0.7390	0.0518	0.5818	0.7759
	114	0.7467	0.0185	0.7282	0.7287	0.0079	0.7104	0.7421
	115	0.9467	0.0488	0.8979	0.9077	0.0348	0.8201	0.9412
	116	0.6914	0.0280	0.6635	0.6625	0.0141	0.6381	0.6878
	117	0.8903	0.0207	0.8696	0.8704	0.0090	0.8505	0.8850
	118	1.0000	0.0692	0.9308	0.9402	0.0502	0.8005	0.9940
	119	0.7994	0.0275	0.7720	0.7736	0.0140	0.7409	0.7945
	120	0.8220	0.0310	0.7909	0.7929	0.0169	0.7518	0.8175
	121	1.0000	0.0891	0.9109	0.9208	0.0637	0.7817	0.9937
	122	0.7025	0.0258	0.6768	0.6772	0.0128	0.6514	0.6986
	123	0.8685	0.0247	0.8438	0.8449	0.0122	0.8161	0.8636
	124	0.8301	0.0341	0.7960	0.7974	0.0183	0.7602	0.8252
	125	0.7081	0.0269	0.6812	0.6829	0.0144	0.6509	0.7032
	126	0.7689	0.0247	0.7442	0.7474	0.0144	0.7127	0.7648
	127	0.8984	0.0205	0.8779	0.8777	0.0079	0.8624	0.8936
	128	1.0000	0.0763	0.9237	0.9199	0.0468	0.8420	0.9938
	129	0.9720	0.0335	0.9386	0.9410	0.0183	0.8938	0.9659
	130	1.0000	0.1054	0.8946	0.9098	0.0810	0.7166	0.9943
	131	1.0000	0.0582	0.9418	0.9507	0.0379	0.8633	0.9938
	132	0.9833	0.0389	0.9444	0.9502	0.0255	0.8773	0.9778
	133	1.0000	0.1371	0.8629	0.9122	0.1305	0.5349	0.9946
	134	0.8256	0.0385	0.7871	0.7897	0.0219	0.7418	0.8211
	135	0.7642	0.0338	0.7303	0.7330	0.0196	0.6855	0.7596
	136	0.8083	0.0257	0.7826	0.7841	0.0124	0.7556	0.8034
	137	0.8179	0.0241	0.7938	0.7939	0.0104	0.7735	0.8130
	138	0.7396	0.0236	0.7159	0.7170	0.0110	0.6936	0.7344
	139	0.8060	0.0166	0.7894	0.7896	0.0068	0.7752	0.8011
	140	0.9816	0.0473	0.9343	0.9401	0.0286	0.8701	0.9760
	141	0.7131	0.0291	0.6841	0.6868	0.0175	0.6467	0.7094
	142	0.9250	0.0296	0.8954	0.8962	0.0135	0.8663	0.9196
	143	0.9298	0.0269	0.9029	0.9033	0.0109	0.8812	0.9246
	144	0.7587	0.0210	0.7377	0.7392	0.0106	0.7156	0.7541
	145	1.0000	0.0525	0.9475	0.9509	0.0313	0.8802	0.9936
	146	0.9277	0.0204	0.9073	0.9067	0.0078	0.8910	0.9221
	147	0.6859	0.0234	0.6625	0.6638	0.0117	0.6375	0.6816
	148	0.8756	0.0272	0.8484	0.8478	0.0119	0.8254	0.8702
	149	0.9575	0.0312	0.9263	0.9274	0.0151	0.8926	0.9510
	150	1.0000	0.0528	0.9472	0.9406	0.0252	0.9071	0.9937
	151	0.8175	0.0170	0.8005	0.8024	0.0087	0.7796	0.8128
	152	0.9624	0.0333	0.9291	0.9299	0.0168	0.8901	0.9562

153	1.0000	0.1323	0.8677	0.8960	0.1124	0.6311	0.9931
154	1.0000	0.1103	0.8897	0.9026	0.0828	0.7397	0.9943
155	0.7801	0.0392	0.7409	0.7451	0.0243	0.6909	0.7755
156	0.9196	0.0340	0.8856	0.8854	0.0165	0.8507	0.9145
157	0.7249	0.0368	0.6881	0.6919	0.0223	0.6402	0.7203
158	0.6874	0.0429	0.6444	0.6562	0.0337	0.5667	0.6837
159	1.0000	0.0403	0.9597	0.9599	0.0181	0.9248	0.9937
160	1.0000	0.0747	0.9253	0.9153	0.0453	0.8474	0.9939
161	1.0000	0.0915	0.9085	0.9055	0.0637	0.7799	0.9950
162	1.0000	0.0971	0.9029	0.9063	0.0725	0.7454	0.9930
163	0.8778	0.0309	0.8470	0.8482	0.0147	0.8164	0.8718
164	0.7620	0.0320	0.7300	0.7309	0.0186	0.6973	0.7579
165	1.0000	0.1038	0.8962	0.8946	0.0725	0.7693	0.9945
166	0.9685	0.0298	0.9387	0.9396	0.0143	0.9051	0.9627
167	0.9715	0.0267	0.9448	0.9463	0.0123	0.9155	0.9652
168	0.9890	0.0342	0.9547	0.9581	0.0202	0.9101	0.9838
169	1.0000	0.0580	0.9420	0.9365	0.0323	0.8856	0.9943

Appendix B–2: Cost efficiency scores and bias corrected estimates of efficiency through bootstrapping approach

Farm Size	DMU	Cost efficiency Score	Bias	Mean	Median	SD	CI Lower Bound	CI Upper Bound
Small farms	1	1.0000	0.0867	0.9133	0.9298	0.0684	0.7901	1.0000
	2	0.9343	0.0288	0.9056	0.9038	0.0229	0.8593	0.9343
	3	0.6747	0.0413	0.6334	0.6302	0.0317	0.5723	0.6747
	4	1.0000	0.0399	0.9601	0.9554	0.0290	0.9117	1.0000
	5	0.9819	0.0603	0.9216	0.9218	0.0471	0.8278	0.9819
	6	1.0000	0.0616	0.9384	0.9534	0.0574	0.8189	1.0000
	7	1.0000	0.0611	0.9389	0.9397	0.0443	0.8489	1.0000
	8	1.0000	0.1200	0.8800	0.8678	0.0890	0.7192	1.0000
	9	0.8958	0.0165	0.8794	0.8838	0.0167	0.8370	0.8958
	10	0.9636	0.0514	0.9121	0.9178	0.0451	0.8296	0.9636
	11	0.6538	0.0484	0.6054	0.6202	0.0494	0.5203	0.6538
	12	0.7313	0.0451	0.6862	0.6953	0.0438	0.5999	0.7313
	13	0.6495	0.0438	0.6057	0.6139	0.0423	0.5106	0.6495
	14	0.5851	0.0224	0.5627	0.5688	0.0207	0.5181	0.5851
	15	0.8676	0.0316	0.8360	0.8412	0.0273	0.7750	0.8676
	16	0.6656	0.0275	0.6382	0.6393	0.0204	0.5988	0.6656
	17	0.5786	0.0376	0.5410	0.5517	0.0382	0.4528	0.5786
	18	0.9556	0.0605	0.8951	0.9107	0.0521	0.7916	0.9556
	19	1.0000	0.0972	0.9028	0.9329	0.0862	0.7312	1.0000
	20	0.8637	0.0432	0.8205	0.8257	0.0383	0.7322	0.8637
	21	0.9571	0.0585	0.8986	0.9116	0.0547	0.7845	0.9571
	22	0.8390	0.0230	0.8160	0.8161	0.0187	0.7751	0.8390
	23	0.7811	0.0286	0.7524	0.7527	0.0266	0.7023	0.7811
	24	0.9546	0.0345	0.9201	0.9304	0.0315	0.8444	0.9546
	25	1.0000	0.0665	0.9335	0.9414	0.0562	0.8042	1.0000
	26	1.0000	0.1151	0.8849	0.8888	0.0899	0.7158	1.0000
	27	0.5837	0.0384	0.5452	0.5509	0.0342	0.4826	0.5837
	28	0.8418	0.0391	0.8028	0.8041	0.0332	0.7290	0.8418
	29	0.6485	0.0202	0.6283	0.6314	0.0185	0.5906	0.6485
	30	1.0000	0.1101	0.8899	0.8544	0.0719	0.7985	1.0000
	31	0.9003	0.0254	0.8750	0.8817	0.0241	0.8223	0.9003
	32	0.9505	0.0252	0.9253	0.9268	0.0217	0.8765	0.9505
	33	0.9114	0.0424	0.8690	0.8721	0.0405	0.7863	0.9114
	34	0.8652	0.0327	0.8325	0.8364	0.0267	0.7820	0.8652
	35	0.7868	0.0165	0.7703	0.7713	0.0131	0.7440	0.7868
	36	1.0000	0.0529	0.9471	0.9405	0.0438	0.8682	1.0000
	37	0.5437	0.0214	0.5223	0.5216	0.0177	0.4865	0.5437
	38	1.0000	0.1402	0.8598	0.8809	0.1278	0.5641	1.0000
	39	0.9804	0.0433	0.9371	0.9398	0.0363	0.8474	0.9804
	40	1.0000	0.1921	0.8079	0.8245	0.1643	0.4571	1.0000
Medium farms	41	0.7087	0.0190	0.6897	0.6938	0.0168	0.6555	0.7087
	42	0.8024	0.0248	0.7777	0.7798	0.0207	0.7354	0.8024
	43	1.0000	0.0409	0.9591	0.9644	0.0362	0.8708	1.0000
	44	0.9050	0.0337	0.8713	0.8699	0.0259	0.8149	0.9050
	45	1.0000	0.2361	0.7639	0.8339	0.2281	0.2673	1.0000
	46	0.8729	0.0190	0.8539	0.8547	0.0146	0.8246	0.8729
	47	0.7251	0.0278	0.6973	0.6920	0.0190	0.6676	0.7251

48	0.8706	0.0160	0.8547	0.8556	0.0136	0.8247	0.8706
49	0.6826	0.0194	0.6632	0.6654	0.0183	0.6195	0.6826
50	1.0000	0.0510	0.9490	0.9848	0.0656	0.7769	1.0000
51	0.8489	0.0327	0.8162	0.8178	0.0289	0.7625	0.8489
52	0.7176	0.0188	0.6988	0.7020	0.0164	0.6633	0.7176
53	1.0000	0.2502	0.7498	0.8101	0.2225	0.2867	1.0000
54	0.9796	0.0350	0.9446	0.9435	0.0295	0.8824	0.9796
55	0.8007	0.0326	0.7680	0.7664	0.0260	0.7180	0.8007
56	0.7655	0.0516	0.7139	0.7192	0.0454	0.6272	0.7655
57	0.7175	0.0190	0.6985	0.6987	0.0152	0.6670	0.7175
58	0.8174	0.0376	0.7797	0.7821	0.0319	0.7177	0.8174
59	1.0000	0.1793	0.8207	0.8422	0.1647	0.4643	1.0000
60	0.9217	0.0360	0.8857	0.8896	0.0319	0.8142	0.9217
61	1.0000	0.1529	0.8471	0.8240	0.1125	0.6884	1.0000
62	0.8217	0.0209	0.8008	0.8021	0.0170	0.7655	0.8217
63	0.8037	0.0310	0.7727	0.7696	0.0219	0.7336	0.8037
64	0.8681	0.0250	0.8431	0.8399	0.0200	0.8083	0.8681
65	0.8864	0.0481	0.8383	0.8441	0.0423	0.7583	0.8864
66	0.7170	0.0233	0.6936	0.6902	0.0180	0.6591	0.7170
67	0.8642	0.0636	0.8006	0.8144	0.0565	0.6910	0.8642
68	0.7686	0.0218	0.7468	0.7489	0.0186	0.7043	0.7686
69	0.6667	0.0345	0.6322	0.6328	0.0274	0.5769	0.6667
70	0.7801	0.0695	0.7106	0.7253	0.0686	0.5397	0.7801
71	1.0000	0.1205	0.8795	0.8730	0.0786	0.7501	1.0000
72	0.8449	0.0181	0.8268	0.8279	0.0153	0.7920	0.8449
73	0.7904	0.0285	0.7619	0.7625	0.0251	0.7084	0.7904
74	0.7363	0.0148	0.7215	0.7207	0.0148	0.7039	0.7363
75	0.7393	0.0225	0.7168	0.7201	0.0206	0.6706	0.7393
76	0.7303	0.0135	0.7168	0.7173	0.0113	0.6913	0.7303
77	0.7955	0.0216	0.7739	0.7792	0.0206	0.7296	0.7955
78	0.7555	0.0137	0.7417	0.7419	0.0114	0.7158	0.7555
79	0.9412	0.0145	0.9266	0.9291	0.0127	0.8961	0.9412
80	0.7609	0.0525	0.7084	0.7251	0.0532	0.6108	0.7609
81	0.8067	0.0297	0.7770	0.7813	0.0274	0.7151	0.8067
82	0.6606	0.0270	0.6335	0.6363	0.0265	0.5839	0.6606
83	0.6089	0.0185	0.5904	0.5915	0.0157	0.5565	0.6089
84	0.6512	0.0305	0.6207	0.6287	0.0296	0.5551	0.6512
85	1.0000	0.1698	0.8302	0.8374	0.1481	0.5062	1.0000
86	0.7604	0.0301	0.7302	0.7273	0.0234	0.6870	0.7604
87	0.6038	0.0173	0.5865	0.5867	0.0148	0.5530	0.6038
88	0.7685	0.0157	0.7527	0.7517	0.0107	0.7329	0.7685
89	0.8611	0.0247	0.8364	0.8374	0.0199	0.7969	0.8611
90	0.6734	0.0142	0.6592	0.6596	0.0113	0.6350	0.6734
91	1.0000	0.0489	0.9511	0.9499	0.0444	0.8626	1.0000
92	0.9323	0.0420	0.8903	0.9024	0.0420	0.7977	0.9323
93	0.8298	0.0147	0.8150	0.8175	0.0153	0.7751	0.8298
94	0.3966	0.0198	0.3768	0.3786	0.0179	0.3397	0.3966
95	0.8576	0.0589	0.7986	0.8151	0.0588	0.6552	0.8576
96	0.7209	0.0292	0.6917	0.6903	0.0268	0.6399	0.7209
97	0.8542	0.0420	0.8122	0.8137	0.0321	0.7439	0.8542
98	0.8991	0.0258	0.8733	0.8848	0.0256	0.8154	0.8991
99	0.7852	0.0241	0.7611	0.7604	0.0172	0.7231	0.7852
100	0.8867	0.0274	0.8593	0.8603	0.0198	0.8170	0.8867
101	0.7783	0.0169	0.7615	0.7646	0.0154	0.7289	0.7783

	102	1.0000	0.1789	0.8211	0.8429	0.1499	0.5495	1.0000
	103	0.6703	0.0454	0.6248	0.6316	0.0411	0.5444	0.6703
	104	0.7689	0.0122	0.7567	0.7562	0.0097	0.7365	0.7689
	105	0.5159	0.0272	0.4887	0.4910	0.0233	0.4475	0.5159
	106	0.5101	0.0151	0.4950	0.4984	0.0143	0.4638	0.5101
	107	0.5455	0.0286	0.5170	0.5190	0.0236	0.4722	0.5455
	108	0.6257	0.0456	0.5802	0.5830	0.0377	0.5057	0.6257
Large farms	109	0.8744	0.0511	0.8233	0.8197	0.0385	0.7513	0.8744
	110	0.7240	0.0258	0.6982	0.6961	0.0221	0.6517	0.7240
	111	0.7618	0.0273	0.7345	0.7406	0.0253	0.6794	0.7618
	112	0.7871	0.0465	0.7406	0.7460	0.0438	0.6430	0.7871
	113	0.5771	0.0509	0.5262	0.5448	0.0611	0.3645	0.5771
	114	0.5170	0.0356	0.4815	0.4845	0.0296	0.4308	0.5170
	115	0.9455	0.0274	0.9181	0.9202	0.0235	0.8707	0.9455
	116	0.6914	0.0334	0.6579	0.6594	0.0317	0.5764	0.6914
	117	0.6894	0.0480	0.6414	0.6593	0.0536	0.5096	0.6894
	118	1.0000	0.1017	0.8983	0.8786	0.0692	0.7995	1.0000
	119	0.7370	0.0174	0.7196	0.7208	0.0160	0.6795	0.7370
	120	0.8918	0.0404	0.8513	0.8537	0.0322	0.7872	0.8918
	121	1.0000	0.0507	0.9493	0.9418	0.0381	0.8713	1.0000
	122	0.5864	0.0300	0.5564	0.5589	0.0274	0.5053	0.5864
	123	0.8735	0.0228	0.8508	0.8472	0.0185	0.8169	0.8735
	124	0.7713	0.0318	0.7395	0.7469	0.0302	0.6695	0.7713
	125	0.6142	0.0364	0.5778	0.5822	0.0351	0.4951	0.6142
	126	0.7468	0.0356	0.7112	0.7181	0.0363	0.6260	0.7468
	127	0.8557	0.0261	0.8296	0.8415	0.0251	0.7800	0.8557
	128	1.0000	0.0663	0.9337	0.9333	0.0521	0.8383	1.0000
	129	0.9816	0.0351	0.9465	0.9490	0.0308	0.8757	0.9816
	130	1.0000	0.1116	0.8884	0.9066	0.0943	0.6664	1.0000
	131	1.0000	0.0535	0.9465	0.9406	0.0361	0.8827	1.0000
	132	0.9407	0.0404	0.9002	0.9109	0.0400	0.7978	0.9407
	133	1.0000	0.2538	0.7462	0.8422	0.2873	0.0500	1.0000
	134	0.8364	0.0320	0.8044	0.8040	0.0227	0.7637	0.8364
	135	0.8504	0.0242	0.8262	0.8265	0.0187	0.7843	0.8504
	136	0.8444	0.0330	0.8114	0.8083	0.0276	0.7542	0.8444
	137	0.6594	0.0437	0.6157	0.6171	0.0371	0.5423	0.6594
	138	0.6688	0.0159	0.6529	0.6539	0.0132	0.6258	0.6688
	139	0.5286	0.0352	0.4934	0.5016	0.0330	0.4121	0.5286
	140	1.0000	0.1081	0.8919	0.8694	0.0699	0.7919	1.0000
	141	0.5731	0.0203	0.5528	0.5493	0.0147	0.5292	0.5731
	142	0.8958	0.0466	0.8492	0.8605	0.0444	0.7472	0.8958
	143	0.8703	0.0250	0.8453	0.8439	0.0185	0.8093	0.8703
	144	0.7153	0.0123	0.7031	0.7041	0.0113	0.6784	0.7153
	145	0.9436	0.0639	0.8797	0.8942	0.0613	0.7480	0.9436
	146	0.7520	0.0251	0.7269	0.7278	0.0190	0.6870	0.7520
	147	1.0000	0.2476	0.7524	0.8314	0.2476	0.0860	1.0000
	148	0.7540	0.0555	0.6985	0.7113	0.0520	0.6045	0.7540
	149	0.7779	0.0392	0.7387	0.7546	0.0437	0.6376	0.7779
	150	1.0000	0.0379	0.9621	0.9702	0.0291	0.8980	1.0000
	151	0.5659	0.0257	0.5402	0.5425	0.0208	0.4959	0.5659
	152	0.9830	0.0416	0.9414	0.9420	0.0323	0.8680	0.9830
	153	1.0000	0.2461	0.7539	0.8293	0.2409	0.2434	1.0000
	154	0.9743	0.0503	0.9240	0.9247	0.0392	0.8573	0.9743

155	0.8011	0.0254	0.7757	0.7746	0.0228	0.7293	0.8011
156	0.8926	0.0306	0.8620	0.8582	0.0227	0.8238	0.8926
157	0.5882	0.0216	0.5666	0.5744	0.0211	0.5176	0.5882
158	0.9889	0.0288	0.9601	0.9650	0.0260	0.9096	0.9889
159	0.9060	0.0333	0.8727	0.8811	0.0293	0.8096	0.9060
160	1.0000	0.0420	0.9580	0.9536	0.0348	0.8780	1.0000
161	1.0000	0.1506	0.8494	0.8546	0.1227	0.5862	1.0000
162	1.0000	0.1805	0.8195	0.8384	0.1627	0.4522	1.0000
163	0.8607	0.0351	0.8255	0.8289	0.0312	0.7664	0.8607
164	0.6464	0.0229	0.6235	0.6260	0.0214	0.5779	0.6464
165	1.0000	0.1358	0.8642	0.8429	0.0991	0.6872	1.0000
166	0.9598	0.0411	0.9187	0.9175	0.0291	0.8544	0.9598
167	0.9049	0.0341	0.8708	0.8752	0.0289	0.8012	0.9049
168	0.9371	0.0517	0.8854	0.8830	0.0398	0.8129	0.9371
169	1.0000	0.1506	0.8494	0.8314	0.1110	0.6884	1.0000

Appendix B–3: Environmental efficiency scores using farm level ad-hoc indicators and bias corrected estimates of efficiency through bootstrapping approach

Farm size	DMU	Environmental efficiency	Bias	Mean	Median	SD	CI Lower Bound	CI Upper Bound
Small farms	1	1.0000	0.0600	0.9400	0.9454	0.0568	0.8083	1.0000
	2	0.9330	0.0242	0.9088	0.9128	0.0238	0.8598	0.9330
	3	1.0000	0.1383	0.8617	0.9288	0.1534	0.4549	1.0000
	4	0.9606	0.0323	0.9283	0.9289	0.0295	0.8695	0.9606
	5	0.9377	0.0289	0.9088	0.9272	0.0362	0.8182	0.9377
	6	0.9754	0.0238	0.9516	0.9642	0.0337	0.8540	0.9754
	7	1.0000	0.0290	0.9710	0.9792	0.0321	0.8876	1.0000
	8	1.0000	0.1206	0.8794	0.9318	0.1230	0.6584	1.0000
	9	0.9976	0.0163	0.9814	0.9904	0.0222	0.9206	0.9976
	10	1.0000	0.0232	0.9768	0.9890	0.0267	0.9175	1.0000
	11	0.8474	0.0346	0.8128	0.8179	0.0343	0.7322	0.8474
	12	1.0000	0.0303	0.9697	0.9711	0.0286	0.9117	1.0000
	13	0.7867	0.0347	0.7521	0.7588	0.0360	0.6614	0.7867
	14	0.9336	0.0256	0.9080	0.9300	0.0319	0.8382	0.9336
	15	1.0000	0.1092	0.8908	0.9288	0.1052	0.6995	1.0000
	16	0.8520	0.0226	0.8294	0.8346	0.0252	0.7667	0.8520
	17	1.0000	0.1372	0.8628	0.9175	0.1520	0.5072	1.0000
	18	0.9599	0.0368	0.9231	0.9351	0.0383	0.8329	0.9599
	19	0.9957	0.0314	0.9644	0.9841	0.0464	0.8270	0.9957
	20	1.0000	0.1049	0.8951	0.9300	0.1002	0.7055	1.0000
	21	1.0000	0.0534	0.9466	0.9453	0.0483	0.8480	1.0000
	22	0.8928	0.0348	0.8579	0.8572	0.0318	0.7919	0.8928
	23	0.9309	0.0086	0.9223	0.9238	0.0090	0.9015	0.9309
	24	1.0000	0.0387	0.9613	0.9748	0.0432	0.8588	1.0000
	25	1.0000	0.0903	0.9097	0.9282	0.0777	0.7761	1.0000
	26	1.0000	0.0996	0.9004	0.9299	0.0938	0.7224	1.0000
	27	1.0000	0.0684	0.9316	0.9400	0.0639	0.8070	1.0000
	28	0.8292	0.0162	0.8129	0.8130	0.0144	0.7838	0.8292
	29	0.6453	0.0097	0.6356	0.6389	0.0101	0.6133	0.6453
	30	1.0000	0.1316	0.8684	0.9297	0.1577	0.4505	1.0000
	31	0.9498	0.0102	0.9397	0.9442	0.0127	0.9080	0.9498
	32	1.0000	0.1167	0.8833	0.9344	0.1196	0.6442	1.0000
	33	0.9087	0.0122	0.8965	0.8975	0.0127	0.8645	0.9087
	34	1.0000	0.1076	0.8924	0.9300	0.1066	0.6978	1.0000
	35	0.7417	0.0289	0.7128	0.7225	0.0319	0.6359	0.7417
	36	0.9576	0.0135	0.9441	0.9490	0.0151	0.9058	0.9576
	37	0.6454	0.0219	0.6235	0.6263	0.0214	0.5768	0.6454
	38	0.6034	0.0168	0.5866	0.5882	0.0161	0.5533	0.6034
	39	0.9737	0.0216	0.9521	0.9580	0.0225	0.8986	0.9737
	40	0.9843	0.0269	0.9573	0.9635	0.0286	0.8820	0.9843
Medium farms	41	0.7575	0.0093	0.7481	0.7514	0.0104	0.7226	0.7575
	42	0.8627	0.0137	0.8490	0.8520	0.0141	0.8155	0.8627
	43	0.8384	0.0197	0.8187	0.8218	0.0200	0.7740	0.8384
	44	0.9711	0.0295	0.9416	0.9457	0.0282	0.8805	0.9711
	45	1.0000	0.1208	0.8792	0.9336	0.1213	0.6493	1.0000
	46	0.8181	0.0185	0.7996	0.7999	0.0170	0.7624	0.8181
	47	0.7589	0.0127	0.7461	0.7512	0.0151	0.7064	0.7589
	48	0.8549	0.0088	0.8461	0.8474	0.0087	0.8270	0.8549

49	0.8043	0.0325	0.7718	0.7840	0.0347	0.6991	0.8043
50	1.0000	0.1225	0.8775	0.9380	0.1399	0.4938	1.0000
51	0.7797	0.0127	0.7670	0.7744	0.0151	0.7340	0.7797
52	0.8745	0.0056	0.8690	0.8702	0.0064	0.8526	0.8745
53	1.0000	0.0813	0.9187	0.9378	0.0842	0.7273	1.0000
54	0.9418	0.0204	0.9214	0.9232	0.0186	0.8761	0.9418
55	0.8796	0.0364	0.8431	0.8463	0.0358	0.7613	0.8796
56	1.0000	0.1128	0.8872	0.9382	0.1177	0.6609	1.0000
57	0.8629	0.0079	0.8550	0.8580	0.0102	0.8330	0.8629
58	0.7920	0.0238	0.7682	0.7858	0.0291	0.7056	0.7920
59	1.0000	0.1554	0.8446	0.8799	0.1632	0.4505	1.0000
60	0.9343	0.0402	0.8941	0.9049	0.0406	0.8093	0.9343
61	1.0000	0.1073	0.8927	0.9401	0.1106	0.6977	1.0000
62	1.0000	0.0901	0.9099	0.9300	0.0863	0.7398	1.0000
63	0.9968	0.0370	0.9598	0.9753	0.0415	0.8705	0.9968
64	0.7951	0.0261	0.7691	0.7840	0.0314	0.6914	0.7951
65	0.9833	0.0132	0.9701	0.9752	0.0140	0.9417	0.9833
66	0.8598	0.0159	0.8439	0.8463	0.0148	0.8143	0.8598
67	1.0000	0.1130	0.8870	0.9288	0.1125	0.6518	1.0000
68	0.8073	0.0131	0.7942	0.7946	0.0128	0.7674	0.8073
69	1.0000	0.0838	0.9162	0.9261	0.0731	0.7581	1.0000
70	0.7771	0.0276	0.7495	0.7599	0.0294	0.6839	0.7771
71	1.0000	0.0342	0.9658	0.9734	0.0347	0.8857	1.0000
72	0.7843	0.0254	0.7589	0.7636	0.0255	0.6990	0.7843
73	0.8209	0.0124	0.8085	0.8137	0.0149	0.7708	0.8209
74	0.7576	0.0194	0.7382	0.7466	0.0220	0.6861	0.7576
75	0.8303	0.0225	0.8078	0.8139	0.0232	0.7601	0.8303
76	0.8162	0.0094	0.8068	0.8106	0.0094	0.7891	0.8162
77	0.9492	0.0222	0.9271	0.9379	0.0308	0.8509	0.9492
78	1.0000	0.0930	0.9070	0.9361	0.0908	0.7295	1.0000
79	1.0000	0.0743	0.9257	0.9288	0.0676	0.7875	1.0000
80	0.7689	0.0076	0.7613	0.7664	0.0098	0.7345	0.7689
81	0.8840	0.0069	0.8771	0.8801	0.0079	0.8585	0.8840
82	0.8546	0.0087	0.8458	0.8507	0.0103	0.8192	0.8546
83	0.8111	0.0062	0.8049	0.8062	0.0061	0.7909	0.8111
84	0.8843	0.0056	0.8787	0.8806	0.0063	0.8629	0.8843
85	1.0000	0.1478	0.8522	0.9258	0.1655	0.4504	1.0000
86	0.8822	0.0072	0.8750	0.8758	0.0070	0.8598	0.8822
87	0.7724	0.0057	0.7666	0.7691	0.0068	0.7507	0.7724
88	0.8674	0.0289	0.8386	0.8501	0.0327	0.7565	0.8674
89	0.8701	0.0135	0.8567	0.8607	0.0143	0.8238	0.8701
90	0.9058	0.0448	0.8610	0.8826	0.0536	0.7307	0.9058
91	1.0000	0.0907	0.9093	0.9270	0.0782	0.7857	1.0000
92	0.9195	0.0216	0.8980	0.9032	0.0219	0.8528	0.9195
93	1.0000	0.1334	0.8666	0.9336	0.1447	0.5205	1.0000
94	0.4821	0.0140	0.4682	0.4733	0.0147	0.4354	0.4821
95	0.9593	0.0275	0.9317	0.9366	0.0290	0.8681	0.9593
96	0.7743	0.0120	0.7623	0.7661	0.0130	0.7301	0.7743
97	0.9385	0.0060	0.9324	0.9336	0.0064	0.9179	0.9385
98	0.7630	0.0273	0.7357	0.7467	0.0296	0.6702	0.7630
99	1.0000	0.0206	0.9794	0.9875	0.0223	0.9289	1.0000
100	0.7843	0.0284	0.7559	0.7717	0.0360	0.6704	0.7843
101	0.7947	0.0097	0.7851	0.7897	0.0109	0.7609	0.7947
102	1.0000	0.0535	0.9465	0.9968	0.0788	0.7417	1.0000

	103	0.6626	0.0153	0.6473	0.6580	0.0196	0.6025	0.6626
	104	0.8591	0.0171	0.8420	0.8467	0.0186	0.7990	0.8591
	105	0.7287	0.0052	0.7235	0.7265	0.0062	0.7088	0.7287
	106	0.7172	0.0062	0.7110	0.7123	0.0066	0.6959	0.7172
	107	0.7529	0.0098	0.7431	0.7497	0.0111	0.7207	0.7529
	108	0.8691	0.0085	0.8606	0.8681	0.0102	0.8388	0.8691
Large farms	109	0.9591	0.0164	0.9427	0.9457	0.0179	0.9032	0.9591
	110	0.8467	0.0151	0.8316	0.8332	0.0154	0.7968	0.8467
	111	0.9694	0.0477	0.9217	0.9293	0.0490	0.8094	0.9694
	112	1.0000	0.1355	0.8645	0.9340	0.1536	0.4907	1.0000
	113	1.0000	0.1451	0.8549	0.9288	0.1743	0.3757	1.0000
	114	0.7457	0.0055	0.7402	0.7418	0.0063	0.7248	0.7457
	115	0.9467	0.0352	0.9114	0.9314	0.0421	0.8161	0.9467
	116	0.6298	0.0073	0.6225	0.6241	0.0081	0.6006	0.6298
	117	0.8671	0.0028	0.8643	0.8670	0.0048	0.8498	0.8671
	118	1.0000	0.1193	0.8807	0.9382	0.1305	0.6057	1.0000
	119	0.7710	0.0175	0.7535	0.7585	0.0178	0.7127	0.7710
	120	0.8054	0.0157	0.7898	0.7964	0.0179	0.7560	0.8054
	121	1.0000	0.0363	0.9637	0.9703	0.0394	0.8519	1.0000
	122	0.8050	0.0429	0.7621	0.7818	0.0547	0.6224	0.8050
	123	0.9450	0.0197	0.9253	0.9278	0.0186	0.8889	0.9450
	124	0.8394	0.0235	0.8160	0.8244	0.0251	0.7634	0.8394
	125	0.6749	0.0113	0.6635	0.6749	0.0139	0.6328	0.6749
	126	0.7689	0.0069	0.7620	0.7665	0.0092	0.7364	0.7689
	127	0.8847	0.0034	0.8813	0.8820	0.0033	0.8747	0.8847
	128	1.0000	0.0564	0.9436	0.9418	0.0495	0.8504	1.0000
	129	0.9588	0.0226	0.9362	0.9393	0.0244	0.8711	0.9588
	130	1.0000	0.0889	0.9111	0.9285	0.0834	0.7410	1.0000
	131	1.0000	0.0772	0.9228	0.9347	0.0740	0.7531	1.0000
	132	0.9590	0.0223	0.9367	0.9428	0.0244	0.8708	0.9590
	133	1.0000	0.1219	0.8781	0.9472	0.1622	0.4505	1.0000
	134	0.8156	0.0193	0.7963	0.8052	0.0212	0.7505	0.8156
	135	0.6922	0.0195	0.6727	0.6761	0.0223	0.6356	0.6922
	136	0.7859	0.0052	0.7808	0.7826	0.0058	0.7665	0.7859
	137	0.6921	0.0141	0.6780	0.6891	0.0177	0.6315	0.6921
	138	0.8174	0.0376	0.7798	0.8086	0.0492	0.6711	0.8174
	139	0.8170	0.0032	0.8137	0.8154	0.0089	0.8028	0.8170
	140	1.0000	0.0574	0.9426	0.9442	0.0473	0.8494	1.0000
	141	0.6654	0.0079	0.6575	0.6588	0.0081	0.6391	0.6654
	142	0.9505	0.0228	0.9277	0.9322	0.0244	0.8624	0.9505
	143	0.8912	0.0033	0.8879	0.8887	0.0036	0.8795	0.8912
	144	0.7564	0.0062	0.7501	0.7540	0.0080	0.7285	0.7564
	145	0.9451	0.0078	0.9373	0.9378	0.0074	0.9216	0.9451
	146	0.9540	0.0078	0.9461	0.9518	0.0124	0.9083	0.9540
	147	0.7021	0.0121	0.6900	0.6932	0.0174	0.6631	0.7021
	148	0.8409	0.0049	0.8360	0.8363	0.0049	0.8233	0.8409
	149	1.0000	0.1243	0.8757	0.9419	0.1550	0.4972	1.0000
	150	0.9238	0.0199	0.9039	0.9117	0.0238	0.8391	0.9238
	151	0.7919	0.0057	0.7862	0.7884	0.0069	0.7707	0.7919
	152	0.9535	0.0187	0.9348	0.9372	0.0185	0.8864	0.9535
	153	1.0000	0.1411	0.8589	0.9175	0.1510	0.4907	1.0000
	154	1.0000	0.1360	0.8640	0.9282	0.1431	0.5550	1.0000
	155	0.8016	0.0214	0.7802	0.7843	0.0204	0.7377	0.8016

156	0.9893	0.0312	0.9582	0.9622	0.0304	0.8883	0.9893
157	1.0000	0.1335	0.8665	0.9340	0.1594	0.4696	1.0000
158	1.0000	0.0438	0.9562	0.9840	0.0545	0.8305	1.0000
159	0.9931	0.0105	0.9826	0.9858	0.0115	0.9547	0.9931
160	0.9864	0.0045	0.9818	0.9854	0.0080	0.9556	0.9864
161	0.9530	0.0192	0.9338	0.9381	0.0203	0.8863	0.9530
162	1.0000	0.0552	0.9448	0.9856	0.0797	0.7354	1.0000
163	0.8974	0.0294	0.8680	0.8726	0.0293	0.8064	0.8974
164	0.8552	0.0287	0.8265	0.8340	0.0309	0.7539	0.8552
165	0.9794	0.0233	0.9561	0.9629	0.0259	0.8902	0.9794
166	0.9346	0.0064	0.9282	0.9292	0.0058	0.9154	0.9346
167	0.9415	0.0076	0.9339	0.9336	0.0073	0.9166	0.9415
168	0.9807	0.0134	0.9673	0.9776	0.0170	0.9270	0.9807
169	1.0000	0.0318	0.9682	0.9639	0.0258	0.9211	1.0000

Appendix B–4: Eco-efficiency scores per 1000 kg of seed cotton bases and bias corrected estimates of efficiency through bootstrapping approach

Farm size	DMU	Eco-efficiency Score	Bias	Mean	Median	SD	CI Lower Bound	CI Upper Bound
Small farms	1	0.3648	0.0867	0.2782	0.2799	0.0405	0.1966	0.3478
	2	0.3620	0.0578	0.3041	0.3085	0.0333	0.2325	0.3570
	3	1.0000	0.7173	0.2827	0.2816	0.4005	-0.4344	0.9262
	4	0.5974	0.0772	0.5202	0.5243	0.0417	0.4287	0.5893
	5	0.2493	0.0763	0.1729	0.1718	0.0346	0.1031	0.2396
	6	0.3571	0.0796	0.2775	0.2814	0.0394	0.1930	0.3406
	7	0.2791	0.0637	0.2154	0.2191	0.0338	0.1408	0.2732
	8	0.8153	0.2595	0.5558	0.5633	0.1304	0.2748	0.7758
	9	0.4250	0.1464	0.2786	0.2759	0.0677	0.1486	0.4061
	10	0.3402	0.0198	0.3204	0.3230	0.0104	0.2959	0.3353
	11	0.6891	0.1785	0.5105	0.5191	0.0894	0.3167	0.6594
	12	0.7455	0.1525	0.5931	0.6051	0.0818	0.4057	0.7154
	13	0.7894	0.3647	0.4247	0.4492	0.1956	-0.0162	0.7442
	14	0.6530	0.0758	0.5772	0.5814	0.0414	0.4866	0.6439
	15	0.5259	0.1365	0.3895	0.3952	0.0610	0.2578	0.5011
	16	1.0000	1.3266	-0.3266	-0.2371	0.9444	-2.5436	0.9458
	17	1.0000	0.8841	0.1159	0.0239	0.4556	-0.6862	0.9507
	18	0.5010	0.1243	0.3766	0.3811	0.0549	0.2523	0.4772
	19	0.4397	0.1421	0.2976	0.2950	0.0552	0.1931	0.4092
	20	0.4314	0.2712	0.1603	0.1805	0.1837	-0.2525	0.4157
	21	0.3728	0.0406	0.3323	0.3356	0.0218	0.2804	0.3641
	22	0.3880	0.0566	0.3314	0.3351	0.0295	0.2691	0.3788
	23	0.4503	0.0367	0.4136	0.4165	0.0216	0.3647	0.4441
	24	0.4375	0.0339	0.4036	0.4064	0.0188	0.3602	0.4303
	25	0.5849	0.2182	0.3667	0.3661	0.1080	0.1517	0.5536
	26	0.4910	0.1250	0.3660	0.3694	0.0585	0.2451	0.4704
	27	0.6376	0.1291	0.5084	0.5159	0.0664	0.3534	0.6145
	28	0.6212	0.2957	0.3255	0.3620	0.1900	-0.0866	0.6019
	29	0.2615	0.0861	0.1754	0.1754	0.0381	0.1010	0.2497
	30	0.5418	0.1762	0.3656	0.3596	0.0820	0.2102	0.5251
	31	0.4260	0.0346	0.3913	0.3940	0.0206	0.3443	0.4207
	32	0.3470	0.0899	0.2571	0.2541	0.0342	0.1923	0.3267
	33	0.1900	0.0159	0.1741	0.1751	0.0087	0.1558	0.1870
	34	0.4018	0.0223	0.3795	0.3825	0.0126	0.3487	0.3966
	35	0.3324	0.0648	0.2676	0.2706	0.0333	0.1981	0.3243
	36	0.5008	0.1502	0.3506	0.3566	0.0701	0.2132	0.4734
	37	0.6038	0.2204	0.3835	0.3887	0.1112	0.1690	0.5789
	38	0.6758	0.1755	0.5003	0.5186	0.1045	0.2713	0.6544
	39	0.4465	0.1122	0.3342	0.3384	0.0495	0.2209	0.4192
	40	0.2832	0.0921	0.1911	0.1907	0.0449	0.0991	0.2734
Medium farms	41	0.1740	0.0254	0.1486	0.1498	0.0132	0.1193	0.1706
	42	0.4809	0.0251	0.4557	0.4588	0.0148	0.4183	0.4749
	43	0.3806	0.0806	0.3000	0.3034	0.0412	0.2153	0.3706
	44	0.8806	0.6070	0.2735	0.3314	0.4003	-0.5892	0.8295
	45	0.5289	0.1283	0.4006	0.4147	0.0804	0.2097	0.5123
	46	0.3427	0.0946	0.2481	0.2473	0.0392	0.1749	0.3248
	47	0.2230	0.0446	0.1784	0.1804	0.0226	0.1303	0.2155

48	0.3919	0.0602	0.3317	0.3339	0.0305	0.2687	0.3826
49	0.6033	0.2215	0.3818	0.4006	0.1204	0.0975	0.5714
50	1.0000	1.0967	-0.0967	-0.0637	0.6832	-1.5560	0.9389
51	0.2051	0.0516	0.1534	0.1538	0.0250	0.1039	0.1995
52	0.7347	0.0519	0.6828	0.6878	0.0290	0.6125	0.7222
53	0.4932	0.1231	0.3702	0.3783	0.0611	0.2387	0.4735
54	0.4821	0.1737	0.3084	0.3172	0.0910	0.1002	0.4617
55	0.4092	0.1398	0.2695	0.2653	0.0695	0.1361	0.3980
56	1.0000	1.3671	-0.3671	-0.3074	0.9151	-2.4385	0.9264
57	0.7377	0.3006	0.4371	0.4286	0.1434	0.1416	0.6994
58	0.3416	0.0505	0.2910	0.2926	0.0244	0.2390	0.3324
59	0.3035	0.1568	0.1467	0.1603	0.0985	-0.0677	0.2897
60	0.3374	0.0487	0.2887	0.2917	0.0253	0.2348	0.3298
61	0.3886	0.1380	0.2506	0.2493	0.0709	0.1068	0.3736
62	0.3649	0.0757	0.2892	0.2904	0.0359	0.2140	0.3538
63	0.3808	0.0362	0.3446	0.3467	0.0201	0.2984	0.3756
64	0.3477	0.1100	0.2377	0.2391	0.0479	0.1423	0.3320
65	0.5604	0.0275	0.5329	0.5364	0.0149	0.4969	0.5524
66	0.4366	0.0786	0.3580	0.3638	0.0411	0.2647	0.4255
67	0.7683	0.2283	0.5399	0.5501	0.1190	0.2976	0.7350
68	0.2744	0.0482	0.2261	0.2274	0.0258	0.1708	0.2702
69	0.9174	0.4111	0.5064	0.5457	0.2317	-0.0269	0.8674
70	0.5961	0.1457	0.4504	0.4532	0.0616	0.3212	0.5632
71	0.2591	0.0559	0.2033	0.2055	0.0277	0.1426	0.2524
72	0.2866	0.0491	0.2375	0.2405	0.0291	0.1765	0.2814
73	0.4977	0.1307	0.3670	0.3725	0.0643	0.2344	0.4835
74	0.3193	0.0802	0.2392	0.2391	0.0394	0.1624	0.3119
75	0.4027	0.1433	0.2594	0.2550	0.0704	0.1303	0.3919
76	0.3604	0.0206	0.3398	0.3424	0.0109	0.3134	0.3541
77	0.7827	0.2695	0.5132	0.5472	0.1620	0.1469	0.7524
78	0.9215	0.1861	0.7353	0.7452	0.0992	0.5102	0.8819
79	1.0000	0.2490	0.7510	0.7615	0.1097	0.5022	0.9502
80	0.2219	0.0657	0.1563	0.1536	0.0319	0.0936	0.2165
81	0.3786	0.0215	0.3572	0.3599	0.0134	0.3252	0.3751
82	0.6076	0.0607	0.5469	0.5511	0.0350	0.4681	0.5991
83	0.4282	0.0458	0.3824	0.3841	0.0237	0.3291	0.4198
84	0.5732	0.0307	0.5425	0.5469	0.0186	0.4955	0.5664
85	0.3616	0.1491	0.2125	0.2253	0.0872	0.0244	0.3475
86	0.4745	0.0484	0.4261	0.4294	0.0264	0.3665	0.4676
87	0.2638	0.0344	0.2294	0.2299	0.0191	0.1898	0.2603
88	0.4804	0.1207	0.3597	0.3623	0.0573	0.2466	0.4675
89	1.0000	0.4703	0.5297	0.5617	0.2513	0.0154	0.9450
90	1.0000	1.0009	-0.0009	0.0549	0.6053	-1.2614	0.9577
91	0.5181	0.1231	0.3950	0.3947	0.0587	0.2756	0.5084
92	0.5501	0.1204	0.4297	0.4328	0.0614	0.3035	0.5357
93	1.0000	1.0279	-0.0279	-0.0881	0.5544	-0.9724	0.9503
94	0.6065	0.1369	0.4696	0.4777	0.0682	0.3212	0.5778
95	1.0000	0.5859	0.4141	0.4359	0.3202	-0.2672	0.9606
96	0.4356	0.0499	0.3857	0.3881	0.0275	0.3268	0.4291
97	0.4230	0.0228	0.4002	0.4036	0.0139	0.3662	0.4183
98	0.2906	0.0830	0.2076	0.2070	0.0423	0.1233	0.2827
99	0.8034	0.1685	0.6349	0.6376	0.0888	0.4517	0.7925
100	0.5015	0.0953	0.4062	0.4111	0.0554	0.2892	0.4937
101	0.2984	0.0678	0.2305	0.2318	0.0328	0.1617	0.2919

	102	0.4628	0.0368	0.4260	0.4321	0.0274	0.3580	0.4606
	103	0.3591	0.0871	0.2720	0.2762	0.0447	0.1667	0.3470
	104	1.0000	1.1338	-0.1338	-0.0618	0.6995	-1.6881	0.9670
	105	0.2185	0.0311	0.1874	0.1894	0.0170	0.1518	0.2136
	106	0.2081	0.0398	0.1682	0.1690	0.0185	0.1318	0.2026
	107	0.3238	0.0186	0.3052	0.3082	0.0116	0.2761	0.3198
	108	0.3359	0.0334	0.3025	0.3034	0.0184	0.2625	0.3310
Large farms	109	0.4574	0.0949	0.3625	0.3679	0.0459	0.2648	0.4370
	110	0.5068	0.0285	0.4783	0.4811	0.0170	0.4370	0.5017
	111	0.8666	0.3711	0.4955	0.5191	0.1960	0.0531	0.8321
	112	1.0000	1.0620	-0.0620	-0.0157	0.5930	-1.1140	0.9236
	113	1.0000	0.9725	0.0275	0.0594	0.5592	-1.1829	0.9527
	114	0.2600	0.0474	0.2126	0.2146	0.0237	0.1653	0.2508
	115	0.4366	0.0669	0.3698	0.3719	0.0359	0.2924	0.4280
	116	0.3530	0.1037	0.2493	0.2470	0.0446	0.1668	0.3421
	117	0.3026	0.0220	0.2806	0.2826	0.0128	0.2505	0.2981
	118	0.3655	0.0627	0.3028	0.3073	0.0311	0.2259	0.3508
	119	0.3922	0.1072	0.2851	0.2892	0.0511	0.1779	0.3777
	120	0.3438	0.0164	0.3274	0.3300	0.0101	0.3018	0.3400
	121	0.4538	0.2763	0.1775	0.1881	0.1632	-0.1452	0.4352
	122	0.5838	0.1937	0.3902	0.3934	0.0862	0.2099	0.5486
	123	0.6701	0.0879	0.5822	0.5929	0.0556	0.4459	0.6577
	124	0.7985	0.0472	0.7512	0.7568	0.0274	0.6877	0.7885
	125	0.2643	0.0205	0.2438	0.2450	0.0110	0.2188	0.2598
	126	0.2729	0.0409	0.2321	0.2346	0.0243	0.1816	0.2689
	127	0.3531	0.0191	0.3340	0.3365	0.0123	0.3054	0.3498
	128	0.9570	0.5820	0.3751	0.4256	0.3447	-0.3935	0.9133
	129	0.4575	0.0782	0.3793	0.3841	0.0416	0.2795	0.4430
	130	0.6087	0.2701	0.3386	0.3448	0.1293	0.0746	0.5757
	131	0.5950	0.1038	0.4911	0.5028	0.0631	0.3528	0.5826
	132	0.4511	0.0822	0.3689	0.3718	0.0435	0.2686	0.4417
	133	0.4088	0.1632	0.2456	0.2480	0.0802	0.0791	0.3890
	134	0.3278	0.1003	0.2275	0.2250	0.0485	0.1290	0.3163
	135	0.5980	0.1180	0.4800	0.4872	0.0639	0.3275	0.5778
	136	0.2980	0.0840	0.2141	0.2154	0.0381	0.1373	0.2861
	137	0.3184	0.0266	0.2918	0.2934	0.0152	0.2587	0.3145
	138	0.6008	0.1201	0.4807	0.4843	0.0539	0.3697	0.5825
	139	0.5062	0.0358	0.4704	0.4742	0.0226	0.4173	0.5002
	140	0.4450	0.1198	0.3252	0.3246	0.0570	0.2059	0.4322
	141	0.2308	0.0273	0.2036	0.2054	0.0153	0.1666	0.2263
	142	0.8208	0.2780	0.5428	0.5520	0.1401	0.2424	0.7849
	143	0.3791	0.0234	0.3557	0.3581	0.0142	0.3206	0.3751
	144	0.4340	0.0359	0.3981	0.4019	0.0219	0.3469	0.4283
	145	0.2955	0.0329	0.2626	0.2636	0.0165	0.2272	0.2897
	146	0.6653	0.0727	0.5925	0.5999	0.0467	0.4788	0.6566
	147	0.3657	0.0721	0.2936	0.2959	0.0376	0.2142	0.3562
	148	0.3018	0.0180	0.2838	0.2855	0.0107	0.2589	0.2981
	149	0.8323	0.2461	0.5862	0.6074	0.1233	0.3043	0.7884
	150	0.2562	0.0481	0.2082	0.2092	0.0234	0.1608	0.2491
	151	0.3842	0.0794	0.3048	0.3062	0.0433	0.2100	0.3744
	152	0.4462	0.0758	0.3704	0.3780	0.0429	0.2614	0.4347
	153	0.3440	0.0324	0.3116	0.3130	0.0177	0.2721	0.3377
	154	0.6049	0.2554	0.3495	0.3484	0.1368	0.0639	0.5851

155	0.3444	0.0775	0.2669	0.2668	0.0355	0.1994	0.3343
156	0.5072	0.1000	0.4073	0.4143	0.0497	0.2889	0.4841
157	0.9286	0.3249	0.6037	0.6476	0.1956	0.1509	0.8839
158	0.9203	0.2233	0.6971	0.7048	0.1108	0.4576	0.8907
159	0.4711	0.0323	0.4388	0.4420	0.0197	0.3926	0.4659
160	0.3290	0.0919	0.2372	0.2378	0.0397	0.1578	0.3182
161	0.3448	0.0348	0.3099	0.3110	0.0188	0.2681	0.3392
162	0.3809	0.0659	0.3150	0.3158	0.0328	0.2410	0.3705
163	0.6347	0.2893	0.3455	0.3294	0.1392	0.0921	0.6094
164	0.5687	0.2412	0.3275	0.3159	0.1078	0.1287	0.5400
165	0.2755	0.0290	0.2465	0.2477	0.0153	0.2149	0.2716
166	0.3443	0.0545	0.2898	0.2908	0.0250	0.2371	0.3316
167	0.3446	0.0281	0.3165	0.3184	0.0162	0.2795	0.3402
168	0.4809	0.0932	0.3877	0.3893	0.0445	0.2962	0.4650
169	0.5473	0.0768	0.4706	0.4710	0.0401	0.3841	0.5372

Appendix B–5: Eco-efficiency scores on per hectare bases and bias corrected estimates of efficiency through bootstrapping approach

Farm size	DMU	Eco-efficiency Score	Bias	Mean	Median	SD	CI Lower Bound	CI Upper Bound
Small farms	1	1.0000	0.1214	0.8786	0.8754	0.0592	0.7629	0.9896
	2	1.0000	0.0945	0.9055	0.9072	0.0433	0.8132	0.9905
	3	1.0000	0.2538	0.7462	0.7720	0.1840	0.3620	0.9910
	4	0.7834	0.0561	0.7273	0.7279	0.0256	0.6756	0.7772
	5	0.9472	0.0702	0.8770	0.8786	0.0355	0.8034	0.9389
	6	0.8889	0.0760	0.8129	0.8156	0.0376	0.7351	0.8832
	7	0.8505	0.0471	0.8034	0.8116	0.0320	0.7228	0.8447
	8	1.0000	0.1713	0.8287	0.8202	0.0967	0.6454	0.9931
	9	0.9245	0.0992	0.8254	0.8265	0.0520	0.7205	0.9194
	10	0.8684	0.0496	0.8188	0.8171	0.0242	0.7727	0.8638
	11	0.7203	0.0938	0.6265	0.6305	0.0581	0.5041	0.7130
	12	0.9913	0.0707	0.9206	0.9276	0.0456	0.8155	0.9832
	13	0.7606	0.1259	0.6347	0.6454	0.0844	0.4505	0.7546
	14	0.7508	0.0633	0.6874	0.6934	0.0371	0.6038	0.7450
	15	0.8841	0.0987	0.7854	0.7851	0.0532	0.6743	0.8789
	16	1.0000	0.3377	0.6623	0.7361	0.2888	-0.0368	0.9932
	17	1.0000	0.3476	0.6524	0.7300	0.2952	-0.0593	0.9914
	18	0.8993	0.0802	0.8192	0.8187	0.0370	0.7447	0.8912
	19	1.0000	0.1347	0.8653	0.8531	0.0641	0.7621	0.9912
	20	0.8951	0.0745	0.8206	0.8237	0.0390	0.7400	0.8893
	21	0.7804	0.0401	0.7404	0.7399	0.0195	0.7009	0.7765
	22	0.7016	0.0564	0.6452	0.6441	0.0283	0.5927	0.6966
	23	0.7777	0.0463	0.7313	0.7329	0.0231	0.6819	0.7732
	24	0.7705	0.0493	0.7212	0.7183	0.0218	0.6822	0.7654
	25	0.9826	0.1112	0.8714	0.8724	0.0599	0.7452	0.9725
	26	1.0000	0.0996	0.9004	0.9000	0.0469	0.8055	0.9893
	27	0.9465	0.1086	0.8379	0.8425	0.0723	0.6793	0.9414
	28	0.9743	0.1296	0.8447	0.8565	0.0815	0.6535	0.9698
	29	0.5096	0.0491	0.4605	0.4600	0.0263	0.4091	0.5060
	30	1.0000	0.1926	0.8074	0.7880	0.1084	0.6325	0.9940
	31	0.8393	0.0391	0.8002	0.8035	0.0227	0.7494	0.8349
	32	0.7985	0.0591	0.7393	0.7390	0.0253	0.6908	0.7927
	33	0.5312	0.0223	0.5088	0.5104	0.0120	0.4817	0.5274
	34	0.6000	0.0321	0.5679	0.5679	0.0161	0.5360	0.5972
	35	0.6171	0.0393	0.5778	0.5776	0.0166	0.5460	0.6126
	36	1.0000	0.2126	0.7874	0.7557	0.1250	0.5709	0.9926
	37	0.6566	0.0782	0.5784	0.5848	0.0529	0.4647	0.6502
	38	0.6343	0.0910	0.5432	0.5514	0.0608	0.3925	0.6297
	39	0.9952	0.0974	0.8977	0.8968	0.0524	0.7911	0.9866
	40	1.0000	0.0964	0.9036	0.9096	0.0530	0.7934	0.9927
Medium farms	41	0.5000	0.0142	0.4858	0.4876	0.0100	0.4623	0.4989
	42	0.6528	0.0388	0.6141	0.6136	0.0166	0.5842	0.6484
	43	0.6399	0.0352	0.6047	0.6048	0.0159	0.5720	0.6352
	44	0.6806	0.0852	0.5954	0.6035	0.0545	0.4750	0.6751
	45	0.7794	0.0592	0.7202	0.7219	0.0285	0.6591	0.7735
	46	0.5917	0.0435	0.5482	0.5481	0.0179	0.5136	0.5849
	47	0.6736	0.0336	0.6400	0.6414	0.0174	0.6077	0.6683
	48	0.6245	0.0530	0.5715	0.5713	0.0265	0.5180	0.6179

49	0.6697	0.0605	0.6093	0.6114	0.0332	0.5410	0.6629
50	1.0000	0.3404	0.6596	0.7339	0.3011	-0.1373	0.9914
51	0.6158	0.0360	0.5798	0.5795	0.0158	0.5485	0.6106
52	0.6957	0.0698	0.6259	0.6325	0.0415	0.5374	0.6896
53	0.9946	0.0775	0.9171	0.9192	0.0417	0.8233	0.9849
54	0.6983	0.0557	0.6426	0.6431	0.0250	0.5920	0.6924
55	0.6350	0.0501	0.5849	0.5855	0.0236	0.5361	0.6303
56	1.0000	0.2987	0.7013	0.7025	0.2087	0.3213	0.9919
57	0.9333	0.1233	0.8101	0.8127	0.0754	0.6602	0.9253
58	0.7094	0.0365	0.6729	0.6728	0.0152	0.6409	0.7027
59	0.6338	0.0545	0.5792	0.5803	0.0263	0.5278	0.6284
60	0.7452	0.0481	0.6971	0.6977	0.0240	0.6513	0.7373
61	0.9259	0.0949	0.8310	0.8423	0.0611	0.7003	0.9174
62	0.6143	0.0451	0.5693	0.5673	0.0210	0.5303	0.6102
63	0.6021	0.0366	0.5656	0.5661	0.0171	0.5306	0.5960
64	0.7612	0.0910	0.6702	0.6751	0.0530	0.5751	0.7536
65	0.9000	0.0513	0.8487	0.8514	0.0284	0.7903	0.8959
66	0.6474	0.0560	0.5914	0.5910	0.0274	0.5381	0.6425
67	0.9607	0.0906	0.8702	0.8724	0.0456	0.7755	0.9501
68	0.6271	0.0339	0.5931	0.5938	0.0150	0.5615	0.6220
69	0.9011	0.1273	0.7738	0.7943	0.0917	0.5610	0.8932
70	0.8920	0.0635	0.8285	0.8281	0.0282	0.7733	0.8853
71	0.6654	0.0316	0.6338	0.6350	0.0144	0.6030	0.6584
72	0.4309	0.0175	0.4134	0.4141	0.0088	0.3948	0.4284
73	0.7070	0.0633	0.6437	0.6437	0.0295	0.5824	0.7015
74	0.5522	0.0406	0.5116	0.5105	0.0170	0.4805	0.5482
75	0.6958	0.0537	0.6421	0.6425	0.0249	0.5933	0.6909
76	0.6000	0.0417	0.5583	0.5557	0.0199	0.5235	0.5971
77	0.8260	0.1209	0.7051	0.7346	0.0913	0.5056	0.8182
78	0.9057	0.1204	0.7854	0.7978	0.0771	0.6111	0.8988
79	1.0000	0.2148	0.7852	0.7639	0.1269	0.5617	0.9950
80	0.6115	0.0424	0.5691	0.5710	0.0230	0.5277	0.6059
81	0.6693	0.0242	0.6450	0.6460	0.0119	0.6191	0.6661
82	0.7130	0.0651	0.6478	0.6504	0.0329	0.5809	0.7069
83	0.6497	0.0521	0.5975	0.5989	0.0263	0.5444	0.6459
84	0.7316	0.0608	0.6708	0.6693	0.0294	0.6119	0.7247
85	1.0000	0.0984	0.9016	0.9059	0.0520	0.7819	0.9898
86	0.6270	0.0453	0.5817	0.5828	0.0208	0.5361	0.6201
87	0.5651	0.0400	0.5252	0.5226	0.0201	0.4890	0.5623
88	0.6084	0.0726	0.5358	0.5429	0.0475	0.4420	0.6037
89	1.0000	0.3069	0.6931	0.7121	0.2280	0.2158	0.9910
90	0.8985	0.1542	0.7444	0.7894	0.1362	0.4091	0.8921
91	0.6662	0.0570	0.6092	0.6106	0.0265	0.5547	0.6592
92	0.8050	0.0629	0.7422	0.7440	0.0312	0.6776	0.7982
93	1.0000	0.3270	0.6730	0.7008	0.2566	0.0795	0.9899
94	0.4817	0.0518	0.4299	0.4328	0.0311	0.3661	0.4783
95	0.9643	0.1422	0.8221	0.8509	0.1021	0.6118	0.9557
96	0.6312	0.0414	0.5898	0.5904	0.0198	0.5483	0.6262
97	0.7473	0.0484	0.6990	0.6990	0.0249	0.6479	0.7425
98	0.6824	0.0568	0.6256	0.6258	0.0262	0.5755	0.6764
99	1.0000	0.2198	0.7802	0.7391	0.1212	0.6007	0.9857
100	0.6874	0.0638	0.6236	0.6243	0.0335	0.5566	0.6797
101	0.6774	0.0366	0.6408	0.6411	0.0159	0.6088	0.6728
102	1.0000	0.1304	0.8696	0.8741	0.0830	0.7150	0.9912

	103	0.6202	0.0638	0.5563	0.5586	0.0346	0.4804	0.6164
	104	1.0000	0.3507	0.6493	0.7225	0.2986	-0.0869	0.9882
	105	0.5143	0.0199	0.4944	0.4954	0.0124	0.4688	0.5124
	106	0.4870	0.0161	0.4709	0.4728	0.0103	0.4472	0.4849
	107	0.5322	0.0403	0.4918	0.4921	0.0214	0.4470	0.5277
	108	0.7200	0.0197	0.7003	0.7037	0.0148	0.6640	0.7186
Large farms	109	0.9554	0.0951	0.8604	0.8615	0.0506	0.7601	0.9478
	110	0.7094	0.0295	0.6799	0.6815	0.0143	0.6490	0.7046
	111	0.7618	0.1075	0.6543	0.6772	0.0808	0.4726	0.7561
	112	1.0000	0.3333	0.6667	0.7011	0.2522	0.0700	0.9907
	113	1.0000	0.3420	0.6580	0.7401	0.2993	-0.0975	0.9940
	114	0.5143	0.0187	0.4956	0.4971	0.0112	0.4702	0.5120
	115	1.0000	0.0942	0.9058	0.9001	0.0442	0.8318	0.9938
	116	0.5038	0.0537	0.4501	0.4498	0.0295	0.3999	0.4997
	117	0.7200	0.0244	0.6956	0.6976	0.0167	0.6589	0.7184
	118	0.8717	0.0785	0.7932	0.7953	0.0422	0.6961	0.8670
	119	0.7340	0.0492	0.6848	0.6850	0.0211	0.6425	0.7276
	120	0.5143	0.0404	0.4739	0.4700	0.0198	0.4404	0.5113
	121	0.9622	0.1383	0.8239	0.8421	0.0959	0.5935	0.9528
	122	0.7234	0.1026	0.6208	0.6273	0.0603	0.4898	0.7163
	123	0.7108	0.0737	0.6371	0.6411	0.0449	0.5439	0.7079
	124	0.6301	0.0743	0.5557	0.5626	0.0448	0.4596	0.6242
	125	0.5040	0.0236	0.4804	0.4810	0.0113	0.4576	0.5010
	126	0.4292	0.0139	0.4153	0.4162	0.0071	0.3991	0.4269
	127	0.6575	0.0240	0.6335	0.6347	0.0151	0.6079	0.6526
	128	1.0000	0.1269	0.8731	0.8701	0.0648	0.7594	0.9919
	129	0.8787	0.0538	0.8249	0.8253	0.0239	0.7761	0.8691
	130	1.0000	0.1237	0.8763	0.8699	0.0579	0.7682	0.9894
	131	0.9805	0.0744	0.9061	0.9066	0.0375	0.8309	0.9688
	132	0.8689	0.0661	0.8028	0.8031	0.0314	0.7407	0.8621
	133	0.7371	0.0622	0.6749	0.6755	0.0308	0.6131	0.7320
	134	0.8465	0.0698	0.7767	0.7818	0.0403	0.6962	0.8391
	135	0.8374	0.1107	0.7267	0.7406	0.0785	0.5571	0.8319
	136	0.4641	0.0248	0.4393	0.4402	0.0126	0.4126	0.4601
	137	0.5455	0.0319	0.5136	0.5130	0.0133	0.4897	0.5412
	138	0.7643	0.0410	0.7233	0.7236	0.0171	0.6878	0.7577
	139	0.6789	0.0394	0.6395	0.6409	0.0195	0.5957	0.6735
	140	0.8921	0.0555	0.8365	0.8364	0.0254	0.7843	0.8857
	141	0.4576	0.0131	0.4445	0.4454	0.0069	0.4286	0.4552
	142	1.0000	0.2969	0.7031	0.7446	0.2229	0.2814	0.9925
	143	0.6567	0.0367	0.6200	0.6205	0.0184	0.5810	0.6512
	144	0.5668	0.0467	0.5200	0.5218	0.0242	0.4688	0.5615
	145	0.8148	0.0437	0.7711	0.7717	0.0187	0.7338	0.8069
	146	0.8005	0.0628	0.7377	0.7413	0.0351	0.6633	0.7941
	147	0.6464	0.0397	0.6067	0.6066	0.0162	0.5753	0.6405
	148	0.5471	0.0243	0.5228	0.5228	0.0115	0.4980	0.5441
	149	0.8249	0.1152	0.7097	0.7167	0.0763	0.5418	0.8187
	150	0.8807	0.0480	0.8327	0.8328	0.0202	0.7941	0.8729
	151	0.7517	0.0845	0.6672	0.6748	0.0531	0.5537	0.7467
	152	0.8327	0.0522	0.7805	0.7808	0.0243	0.7313	0.8254
	153	0.8342	0.0428	0.7914	0.7918	0.0189	0.7541	0.8299
	154	1.0000	0.2153	0.7847	0.7560	0.1273	0.5918	0.9929
	155	0.5694	0.0420	0.5274	0.5278	0.0205	0.4865	0.5646

156	0.6505	0.0789	0.5716	0.5713	0.0429	0.4802	0.6434
157	0.9047	0.1257	0.7790	0.8023	0.0962	0.5483	0.8956
158	0.9504	0.1207	0.8298	0.8374	0.0716	0.6829	0.9408
159	0.9373	0.0634	0.8739	0.8714	0.0280	0.8220	0.9279
160	1.0000	0.1939	0.8061	0.7772	0.0987	0.6526	0.9926
161	0.8219	0.0474	0.7745	0.7744	0.0197	0.7354	0.8156
162	0.8771	0.0551	0.8220	0.8229	0.0257	0.7684	0.8702
163	0.8320	0.1021	0.7299	0.7360	0.0634	0.5936	0.8247
164	0.6723	0.0810	0.5913	0.5960	0.0463	0.4947	0.6669
165	0.9161	0.0640	0.8521	0.8491	0.0304	0.7978	0.9083
166	0.8671	0.0559	0.8112	0.8129	0.0260	0.7535	0.8596
167	0.7833	0.0562	0.7272	0.7280	0.0275	0.6721	0.7781
168	0.9715	0.1362	0.8353	0.8486	0.0899	0.6805	0.9610
169	1.0000	0.1702	0.8298	0.8352	0.0954	0.6684	0.9902

Appendix C:

Questionnaire

Questionnaire no……………..

Date………/………/…………

Name of the farmer: ________________________ Telephone No: _________________

Village: ___________________________________ Sub District: _________________

A. Farming family and farm household information

1. Age of the head of farming family: _____________years

2. Education of the head of farming family.

(1) Primary (2) Secondary (3) Vocational (4) Bachelor (5) Post graduate (6) any other

4. Total cultivated area under cotton crop___________________acres.

5. Owned area _______________acres, leased area under cotton crop____________acres.

6. Rent rate per acre of leased land______________________Rs/acre.

B. Irrigation System

1. How do you irrigate your cotton field?

(a) Canal water (b) tube well (c) Canal + tube well

2. Type of tube well

(b) Diesel tube well (c) electric tube well (d) Tractor tube well (e) Rent

3. Year of installation_________________5) Cost of installation_________________

4. Characteristics of the pumps used to irrigate cotton crop

Pumps	Size (hp)	No. of Irrigation	Working period (hours/acre)	Delivery of the Pump	Avg. electricity or diesel consumption/ hour	Cost
Electric						
Diesel						
Tractor						

5. If you buy water from the neighboring farmers, please provide the detail.

a) Diesel pump a) Electric pump

c) Horse power of the pump?__________ d) Hours used per acre_______________

e) Cost per hour____________(Rs.)

6. Frequency of water channel maintenance _____________time during cotton crop growth.

7. Required labor/hours to maintain water channel_________________ per time.

8. No. of hours to maintain water channel ___________and length of water channel______

9. Drainage system in the field. a) Yes b) No

10. Irrigation Scheduling:-

Total No. of irrigation	Ist irrigation after sowing (No. of days)	Gap (no. of Days) of remaining irrigation	last irrigation (Date)

C. Farm Machinery

1. Which machinery do you use in cotton crop production at your form?

Machinery/ equipment	Brand/ Model	Size (hp)	Year of purchase	Avg. Fuel consumption per hour use
Power sources				
Tractor				
Tractor				
Other, please specify				

D. Cultural practice and the use of labor, machinery and seed in cotton production.

I. Primary Tillage

1. Primary tillage performed in the area under cotton crop with machinery

Tractor	Name of implement	No. of tillage operations	Hours/acre	Fuel consumption/ hour	Starting date
					……/……../…….
					……/……../…….
					……/……../…….
					……/……../…….
					……/……../…….
					……/……../…….

2. What is hiring rate of the tractor if hired______________________?

3. How many labor involved per acre in primary tillage operation____________________?

4. What is the hiring rate of the labor involved in primary tillage operations___________?

II. Leveling.

1. Leveling performed in the area under cotton crop

Tractor	Name of implement	Hours/acre	Fuel consumption/ hour	Hiring rate (Rs/hr)	Date
					……/……../…….
					……/……../…….
					……/……../…….
					……/……../…….

III. Band making

How do you make bands? a) With tractor b) manually

1. Mechanical band making

Tractor	Name of implement	Total hours/acre	Fuel consumption/ hour	Hiring rate of tractor if rented (Rs/hr)

2. How many labor hours are required to make bands/acre_______________for cotton crop.

3. Hiring rate of the labor_____________and hours of work per day_______________________

IV. Secondary tillage and seedbed preparation

1. Secondary tillage performed in the area under cotton crop with owned machinery

Tractor	Name of implement	No. of tillage operations	Hours/acre	Fuel consumption/ hour	Starting date
					………/……../…….
					………/……../…….
					………/……../…….
					………/……../…….
					………/……../…….

V. Furrowing

1. Machinery and implement used for furrowing in the area under cotton crop.

Tractor	Name of implement	Hours/acre	Fuel consumption/ hour	No. of Labor

VI. Herbicides before sowing

1. Method of application of weedicide. a) Boom sprayer b) manual

2. Hours/acre if applied with tractor

Name of weedicide	Company name	Amount liter or kg/ acre	Cost/Acre	Labor/acre

VII. Delinting

Acid/40 kg of seed	Cost of acid/40 Kg	Labor used/40Kg	Cost if delinted with machine

VIII. Seed Treatment

Type of poison	Amount liter or Kg/40 kg of Seed	Cost of Poison	Labor hour for seed poisoning

IX. Which sowing method do you use?

a) bed sowing b) drill sowing

1. Machinery and implement used for planting operation of cotton.

Sowing date	Tractor + Implement	Own machinery			Hired machinery	
		Working time hours/acre	Labor with machinery	Fuel consumption Liter/hr	Hiring rate (Rs/hr)	Working period (hours)
……/…../….						
……/…../….						
……/…../….						
……/…../….						

2. Labor input for manual sowing of cotton.

Total area (acres)	Method of sowing	No of labor/ acre	Working period hours/acres	Hiring rate of labor (Rs/ day)
	by hand			
	dibbling			

3. Seed input

Item	Variety	Source of seed purchase	Applied rate (kg/acre)	Unit price (Rs./kg)
1.Seed				

4. Labor used for thinning of cotton plant.

No of labor/ acre	Working period hours/acre	Hiring rate (Rs./day)	No. of hours/day

5. Farmyard manure application in the area under cotton crop.

Application date	(acre)	Applied rate (kg/Acre)	Labor hours/ application/acre	Hiring rate	Total amount (kg)
…../…../….					
…../…../….					
…../…../….					

E. Crop care or intercultural

I. Fertilization

1. Fertilizer input in the area under cotton crop

Number	Date	Applied rate (bags/acre)	Types of fertilizer used	Unit price (Rs/bag)
	…../…../….			
	…../…../….			
	…../…../….			
	…../…../….			
	…../…../….			
	…../…../….			
	…../…../….			

2. Man hours/acre of fertilizer application if applied manually________________________?

3. Time required if fertilizer is applied with tractor__________________________________?

II. Mechanical weed control

1. Mechanical weed control in the area under cotton crop.

No of application	Date of application	Machinery/implement used
1	……/……../…..	
2	……/……../…..	
3	……/……../…..	
4	……/……../…..	
5	……/……../…..	
6	……/……../…..	
7	……/……../…..	

III. Chemical weed control *(pre and post emergence application must be identified)*

1. Herbicide application in the area under cotton crop *(Additional Sheet must be attached if required.)*

No	Date of Application	Area (acres)	Company name	Name of herbicide	Applied rate (liter/acre)	Unit price (Rs/l)
1	…../……/…..					
2	…../……/…..					
3	…../……/…..					
4	…../……/…..					
5	…../……/…..					
6	…../……/…..					
7	…../……/…..					
8	…../……/…..					

2. Method of application.

a) Knapsack sprayer   b) hand sprayer   c) with tractor

3. Labor hours to apply per acre of cotton field if applied manually___________________?

4. Hiring rate of labor to apply Herbicides____?

5. How much time is required per care if applied with tractor________________________?

IV. Chemical, insecticide control on cotton crop

1st 2nd, ----------- Application

No	Date of Application	Name of the insect	Insecticide type	Company Name	Applied rate (pack/acre)	Quantity/pack	Unit price (Rs/pack)
1	…../……/…..						
2	…../……/…..						
3	…../……/…..						
4	…../……/…..						
5	…../……/…..						
6	…../……/…..						
7	…../……/…..						
8	…../……/…..						
9	…../……/…..						
10	…../……/…..						
11	…../……/…..						
13	…../……/…..						
14	…../……/…..						

Please use extra pages if needed

2. Method of application.

a) Knapsack sprayer b) hand sprayer c) with tractor (boom sprayer)

3. Labor hours to apply insecticides per acre if applied manually________________________?

4. How much time is required per care if applied with tractor__________________________?

7. Type of tractor used_______________________

F. Picking

1. Picking area and starting date

No	Area	Starting date	No of labor (person/acre)	Working period (hours/acre)	Hiring rate (Rs/ Kg)
1		…/……../…….			
2		…/……../…….			
3		…/……../…….			
4		…/……../…….			
5		…/……../…….			
6		…/……../…….			

2. How long is the average working hour per day of the hired labor?.........................hr/day

3. Cotton yield

Total yield (kg/acre)	Selling price (Rs/kg)	Total production of the farm

4. Sale and transportation

To Ginning factory		**To middle man at farm gate**		**To market**	
Quantity	Price (Rs/kg)	Quantity	Price (Rs/kg)	Quantity	Price (Rs/kg)

5. Distance of ginning factory from field. Average ________________________km?

6. Distance of market from field. Average _______________________________km?

7. Labor input for loading and unloading

No. of loads	Quantity/load	No of labor (person/load)	Working period (hr/load)	Hiring rate

8. Type of machinery and implement used:

(1) Agricultural truck (2) Small tractor + trailer

(3) Big tractor + trailer (4) other…………….

9. What is the average fuel consumption to transport one load_______________?

10. What kind of packaging material you use to pack the raw cotton_________________?

____

Please explain the use of cotton sticks?

1) Use as fuel wood 2) Burn in the field
3) Store somewhere in the field 4) other please specify_______________________

11. Sale of cotton sticks if practiced?

Plot no.	SALE	
	Amount	Price/unit
1		
2		

III. Problem, need and opinion of farmers in crop production

1. What are the problems in crop production for following operations?

1.1 Seedbed preparation for seedling…………………………………………………..

…………………………………………………………………………………………….
……………………………………………………………………………………………..

1.2 Land preparation…………………………………………………………………

…………………………………………………………………………………………….
……………………………………………………………………………………………..

1.3 Planting……………………………………………………………………………
……….………………………………………………………………………………
……….………………………………………………………………………………

1.4 Crop care ……………………………………………………………………...

……………………………………………………………………………………….……

1.5 Picking……………………………………………………………………………...
………..………………………………………………………………………………

1.6 Cutting of the sticks……………………………………………………………...

……………………………………………………………………………………………..

1.7 Transportation………………………………………………………………………..
.………………….……………………………………………………………………

1.8 Other ……………………………………………………………………………..

…………………………………………………………………………………………….

Thanks for your time